1993 _ 25

INTERCOMPARISON OF TWO SYSTEMS FOR CONTINUOUS MEASUREMENT OF RADON-FLUX DENSITY

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ABSTRACT

The ability to monitor radon-flux density continuously is of great value in elucidating radon-transport mechanisms. Intercomparisons of two radon-flux measurement systems were conducted in one of the two test structures operated by Colorado State University (CSU). Systems used by the U.S. Department of Energy Grand Junction Projects Office (GJPO) Radon Laboratory and the CSU investigators are similar in that each uses a flow-through collector sealed to the measurement surface with the collector outflow connected to a continuous radon monitor. Configuration of the collectors is the principal difference between the two systems. The collector for the GJPO system is cylindrical with a relatively large volume and a low ventilation rate (0.5 h^{-1}). The CSU system uses a thin plate-like collector with a small volume and a high ventilation rate (8 h^{-1}). Because of the high ventilation rate, the CSU system is sensitive to the presence of thoron (^{220}Rn). Results from the two systems exhibit good agreement when the CSU system incorporates a thoron filter (a delay line between the collector and the CRM).

INTRODUCTION

The ability to monitor radon-flux density continuously from a surface within a structure has proven to be a valuable tool in understanding the radon transport mechanisms operating in a given situation. As an example, Kendrick and Langner (1991) found a strong relationship between differential pressure across the structure boundary and the radon-flux density for several houses studied in the Grand Junction, Colorado, area. An interesting result of the data analysis was that the so called pressure-driven flow component of the radon-flux accounted for only a small fraction (20%) of the average flux.

The radon research group led by Dr. T. B. Borak of Colorado State University (CSU) evaluated factors affecting radon entry into the two radon test structures located near the CSU campus (Ward et al., 1993). Ward et al. separated the radon entry into two terms: one that correlated with changing differential pressure and a second that persisted even when the structure was overpressurized. This persistent term accounted for more than 80% of the radon entering the test structures under average wind conditions.

CSU has the ability to measure not only the radon-flux density over small selected portions of the structure boundary but also the global radon entry rate for the structure. The measurements made by Ward et al. exhibited little dependence on pressure differentials induced by the stack effect. The most significant variations in radon entry rates correlate with wind events. In the work of Kendrick and Langner (1991), the measured radon-flux density exhibited significant fluctuations attributable to stack-effect-induced pressure differentials. Less frequent wind-induced

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pressure differentials also were observed to affect the radon-flux density. In addition, these wind events affected the radon concentrations indoors and in the soil gas.

Because of the similarities and differences the two groups observed in separate investigations, a direct intercomparison of the two measurement techniques was conducted to ensure the comparability of both group's results.

METHODS

Description of the CSU Radon Test Structures

Grand Junction Projects Office (GJPO) Radon Laboratory and CSU personnel decided to conduct the intercomparison at one of the two radon test structures operated by CSU. Principal among the reasons was the detailed and complete knowledge concerning the various parameters of the structure related to radon transport and entry. The CSU radon test structures are two identical basement structures situated on the southern end of the CSU campus.

Fig. 1 shows a typical cross section of the western structure where the intercomparisons were conducted. The structure is essentially a miniature basement (interior dimensions of 3.35 m by 3.35 m and a wall height of 2.3 m) built using standard construction techniques. The floor slab is 10 cm thick and rests on a bed of gravel approximately 15 cm thick. An eight-mil polyethylene vapor barrier is in place between the floor slab and the gravel bed. The walls were poured as a single unit so there are no wall-to-wall joints and a single floor-wall joint. During construction, the building site was excavated an additional 2 m around and below each structure. Soil from the excavations for both structures was collected, blended, and alternately replaced in 6-inch (15 cm) lifts to ensure that the soil surrounding the structures was as similar as possible.

The basements are completed with a hip roof and interior ceiling. The structures are exceptionally well sealed and, during these experiments, exhibited ventilation rates of approximately 0.03 h^{-1}, compared with approximately 1 h^{-1} for conventional housing. Although the structures can be operated with higher ventilation rates, ongoing experiments being conducted by CSU required low ventilation rates. Any human entry into the structure dramatically affects the ventilation rate as well as other parameters related to radon entry. Because data collection was controlled by a computerized system, it was possible to conduct individual experiments of 1 to 2 weeks in length.

All of the experiments conducted for this project were performed in the western structure. In this structure, a baseboard plenum system covers the entire floor-wall joint and is separated into several distinct sections. The plenum is approximately 8 cm high, and protrudes from the wall approximately 4 cm. Eight openings in the plenum can be capped to isolate the floor-wall joint or can be left open to allow air exchange between the plenum and the room.

The experimental plan was to intercompare concurrent measurements of the radon-flux density from two adjacent portions of the floor slab using the measurement technique developed by the GJPO Radon Laboratory and the technique developed by CSU.

GJPO Radon Laboratory Technique

The technique developed by the GJPO Radon Laboratory is a modification of the flow method described by Collé et al. (1981). As shown in Fig. 2, the GJPO device consists of a cylindrical metal collector that is 0.44 m in diameter and 0.15 m in height and has a volume of approximately 22.8 L. Caulking material seals the open end of the collector to the surface to be measured. A small pump mounted inside the collector provides a continuous sample of the air within the collector to a continuous radon monitor at a flow rate of approximately 0.2 L min^{-1}. This flow rate (Q_m in the equations) is monitored continuously by a volumetric flow meter. A 1-inch hole in the side of the collector opposite the pump allows room air to backfill the collector as sample is withdrawn. When operated at this flow rate, there is no measurable differential pressure (< 0.2 Pa) between the collector interior and the room. The ventilation rate of the flux collector is approximately 0.53 h^{-1}.

The collector acts as a partial accumulator and allows the radon concentration to build up within the collector to a concentration that is a function of the radon flux into the collector, the concentration of radon in the air backfilling the collector, and the rate of airflow through the collector. A simple mass balance approach, neglecting the radioactive decay of radon, yields the following expression for the measured radon-flux density:

$$J = \frac{Q_s C_s + E}{A} = \frac{Q_m C_m - Q_r C_r}{A}, \tag{1}$$

where

J = radon-flux density from the surface of interest,
Q_s = flow rate of soil gases into the collector,
C_s = radon concentration of the soil gases,
E = contribution of radon from direct emanation,
A = area of the collector,
Q_m = flow rate of air from the collector,
C_m = radon concentration in the collector,
Q_r = flow rate of room air into the collector, and
C_r = radon concentration of the room air.

The rate of air flow out of the collector is equal to the rate of air flow into the collector, $Q_m = Q_s + Q_r$. If the assumption is made that Q_s is small compared with Q_r, that is to say that $Q_m \approx Q_r$, then the net radon-flux density from the surface being measured may be approximated by

$$J = \frac{Q_s C_s + E}{A} = \frac{Q_m (C_m - C_r)}{A}. \tag{2}$$

Therefore, the following equation was used to calculate the measured radon-flux density:

$$J = \frac{Q_m (C_m - C_r)}{A}. \tag{3}$$

Equation (3) shows that as C_r increases in magnitude (i.e., higher radon concentrations in the room), the uncertainty in (C_m - C_r) increases. One way of reducing this uncertainty is to supply air with a low radon concentration to backfill the flux collector. To accomplish this, a manifold was adapted to the flux collector that allows atmospheric air, or other conditioned air, to be delivered to the hole in the side of the collector without affecting the differential pressure between the collector interior and the room. A small pump, mounted 1 m above ground level adjacent to the west structure, was used to supply atmospheric air to the manifold.

The manifold consists of a length of 1 1/4-inch PVC pipe connected to the flux collector with a "T" connector. One end of the pipe is fitted with a hose barb to accept 1/4-inch rubber tubing, and the other end of the pipe is open to the room. The exhaust from a continuous radon monitor sampling outside air is directed into the manifold through the hose barb. Maintaining a flow rate of 0.4 L min^{-1} of atmospheric air to the manifold ensures that the radon concentration within the manifold remains at the outdoor concentration, even as the flux collector draws the 0.2 L min^{-1} required to balance the flux collector sample outflow.

The continuous radon monitors employed by GJPO were built using a portable scaler connected to a 3-inch photomultiplier tube, facing into the end of a 1-L, zinc sulfide-coated scintillation chamber. Modifications were made to the scalers to output a logic-level pulse that could be counted by the associated data logger. Counts from the radon monitors were accumulated over a 15-minute period, and calibration constants were applied to determine the radon concentration. Laminar flow elements, with differential pressure transducers, were used to measure the various flow rates. The outputs of the pressure transducers were connected to the data logger with 1-minute measurements averaged over the 15-minute record interval.

In addition to those parameters directly associated with the radon-flux density measurements, a number of other parameters were monitored to describe the behavior of the test structure more completely. These parameters included inside and outside temperatures, sub-slab radon concentration, outside radon concentration, barometric pressure, and several differential pressures across the structure shell. Details of the instrumentation and data logging system used by GJPO are in Kendrick and Langner (1991).

CSU Measurement Technique

The CSU measurement method is similar in many respects to the technique developed by the GJPO Radon Laboratory with the principal difference being the configuration of the flux collector. A plate-like device fabricated from a 1/2-inch-thick sheet of Plexiglass with a 6-mm (1/4 inch) cavity milled in one side is used for the collector. The footprint of the collector is 0.12 m^2 and it has a volume of approximately 0.72 L as compared with 22.8 L for the GJPO collector. A pump mounted externally to the collector plate draws sample from one end of the collector through a continuous radon monitor and a mass flow meter at 0.1 L min^{-1}. Room air backfills the collector through a small hole in the other end as sample is withdrawn. A pressure transducer was used to verify that the differential pressure between the collector and the room never exceeded ± 0.1 Pa. The ventilation rate for the CSU collector is approximately 7.2 min^{-1}, as compared to 0.53 h^{-1} for the GJPO device. The mass-flow meter was calibrated for the air density at Ft. Collins. Fig. 3 is a schematic diagram of the CSU apparatus used for the later measurements; initial measurements were conducted without the thoron delay line. Data from the CSU device was reduced using equation (3). Specific details of the various instrumentation used by CSU are in Ward et al. (1993) and Ward and Borak (1991).

RESULTS AND DISCUSSION

Comparison of the two measurement techniques was initiated by comparing the measurement results of indoor radon concentration obtained by the two laboratories. Fig. 4 shows a time plot of the measurement results of room radon concentration for the two laboratories. Results reported by GJPO are consistently higher than the CSU results.

Fig. 5 presents the results of a linear regression of the data shown in Fig. 4. The slope of 0.93 indicates a 7% bias in calibration between the two laboratories. Results from other measurement intervals exhibit similar results. This level of agreement is certainly within an acceptable margin of error for environmental radon measurements conducted with field instruments. Measurements of other radon concentrations, such as outside air, show similar agreement.

Unexpectedly, initial measurements of the radon-flux density from the two techniques showed significant disagreement. The results reported by CSU were more than a factor of two higher than the GJPO results. This discrepancy existed for quite some length of time, with both laboratories checking and rechecking equipment installation and calibration, etc. After considerable effort on the part of both laboratories, the discrepancies were suspected to be attributable to the presence of thoron because the major difference between the two devices was the ventilation rate.

Thoron (^{220}Rn) has a half life of only 56 seconds compared with the 3.8-day half life of radon (^{222}Rn). The short half life of thoron combined with the relatively low ventilation rate of the GJPO device results in all of the thoron decaying by the time the air sample reaches the continuous radon monitor. The air sample from the CSU device, on the other hand, has a significantly shorter travel time from the collector to the radon monitor in the initial configuration (without the thoron delay line). This shorter travel time allows significant quantities of thoron to be delivered to the scintillation chamber. Consequently, significant numbers of counts attributable to ^{220}Rn and its short-lived progeny were registered because the continuous radon monitor can not differentiate between the alpha-decay events that are due to ^{222}Rn and its short-lived progeny and those of ^{220}Rn.

Once the problem was recognized, it was a simple matter to install a thoron filter on the CSU device. The thoron filter is essentially a delay line installed between the collector and the radon monitor. The extra length of tubing in the delay line (≈ 15 m) adds approximately 5 minutes to the time required for the air sample to reach the radon monitor. This additional 5 minutes is sufficient to allow virtually all of the thoron to decay. Fig. 6 shows a time plot of the results from the GJPO device compared with the results from the CSU device with and without the thoron filter. The two techniques show good agreement when the thoron filter is installed on the CSU device.

During the course of the intercomparison measurements, the baseboard plenum was both open and closed. In the open position, radon exhaling from the floor-wall joint is allowed to enter the room and ultimately is ventilated to the atmosphere. With the plenum closed, this route of escape is not available, and the radon concentration in the sub-slab air space increases, increasing the radon concentration gradient across the floor slab. The higher radon concentration gradient results in a higher flux through the floor slab.

Fig. 7 shows a box-and-whisker plot of typical intercomparison results with the baseboard plenum open and closed. In the box-and-whisker plot, the box encloses the interquartile range (second and third quartiles) and the horizontal line shows the median. The whiskers are plotted to include a range of 1.5 times the interquartile range. Data lying outside the whiskers are plotted as individual points.

Of significance is the magnitude of the thoron signal detected by the CSU measurement system. Although this system was not calibrated for ^{220}Rn, it is readily apparent that the ^{220}Rn entering through the floor was approximately equal to that of ^{222}Rn. This example serves to remind us that thoron must not be ignored during "routine" measurements of radon.

CONCLUSIONS

The techniques employed by CSU and GJPO to measure radon-flux density show good agreement when a thoron filter is employed in the sample line between the collector and the continuous radon monitor on the CSU apparatus.

The response of the unfiltered CSU apparatus emphasizes two important points. First, thoron (^{220}Rn) is probably present in most of the environments in which radon measurements are conducted, whether or not one is looking for thoron. Second, most instruments designed to measure gaseous radon (^{222}Rn) are sensitive to thoron (^{220}Rn) to some degree. This sensitivity should be considered carefully when planning measurements and interpreting the results.

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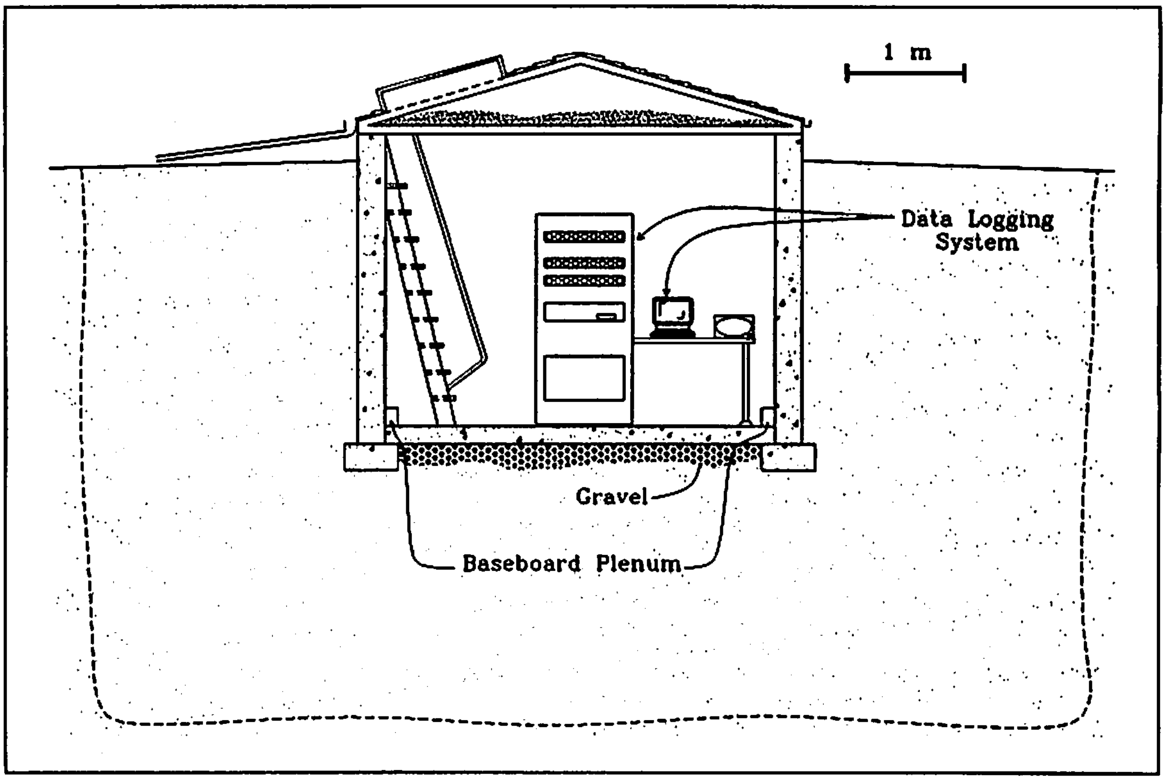

Fig 1. Cross-section of one of the radon test structures near the CSU campus; dashed line indicates limit of excavation during construction.

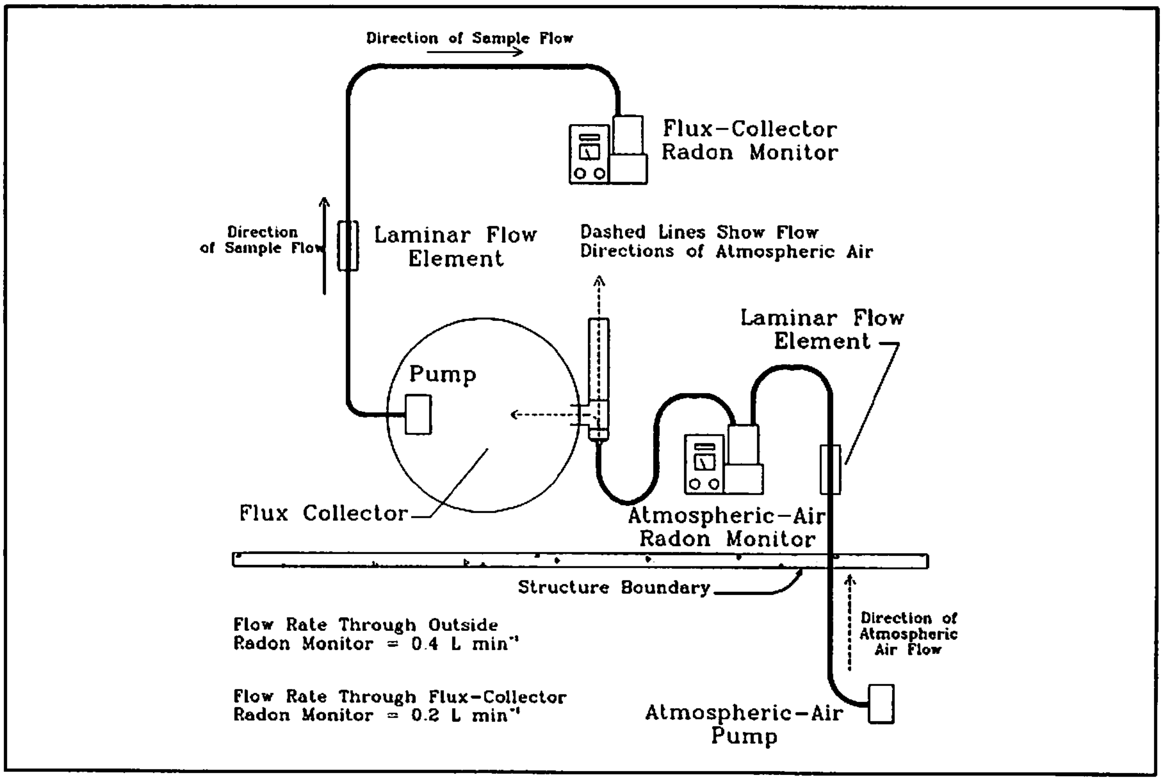

Fig 2. Schematic diagram of the apparatus used by GJPO to measure radon-flux density.

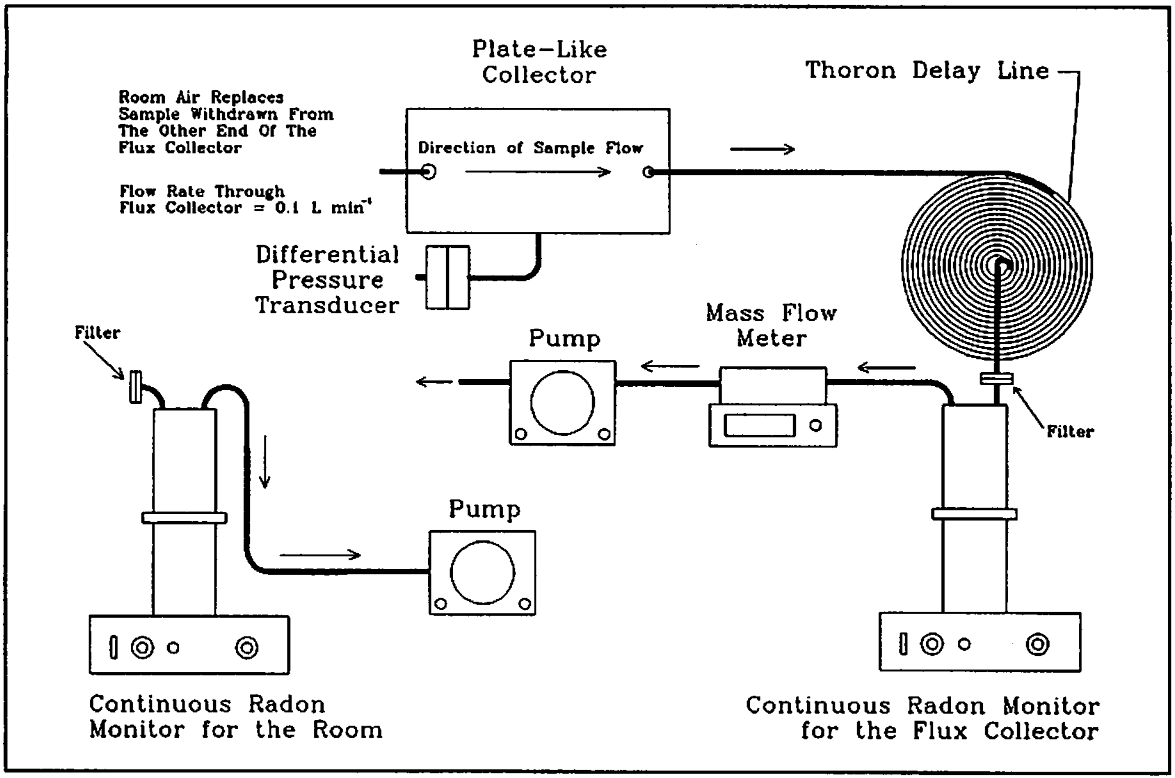

Fig. 3. Schematic diagram of the apparatus used by CSU to measure radon-flux density. The thoron delay line was a modification used in the later measurements.

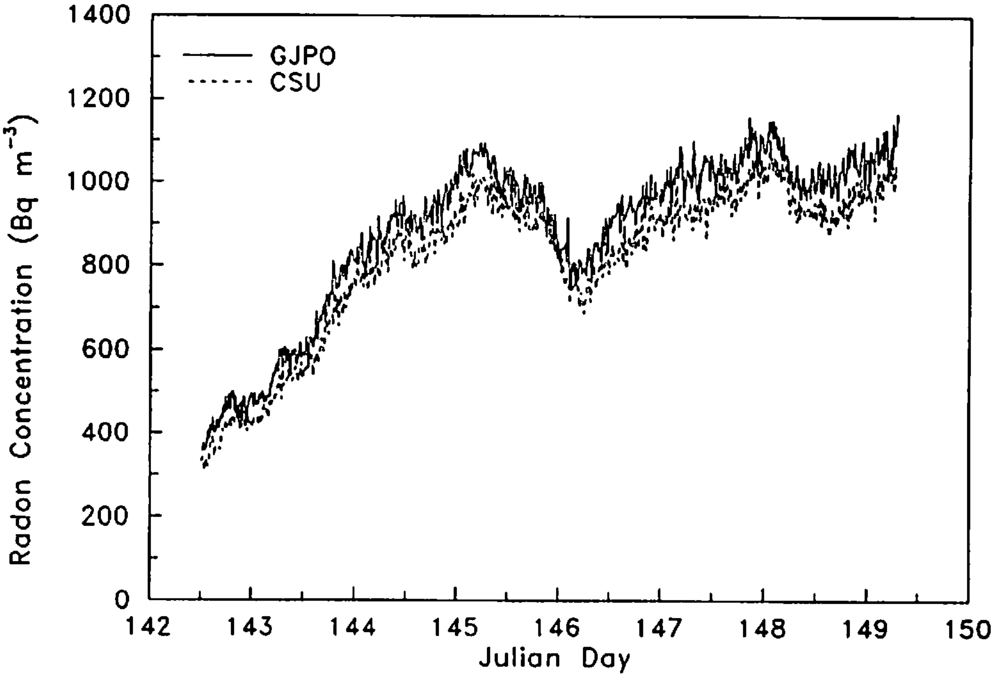

Fig. 4. Time plot of indoor radon concentrations measured by CSU and GJPO.

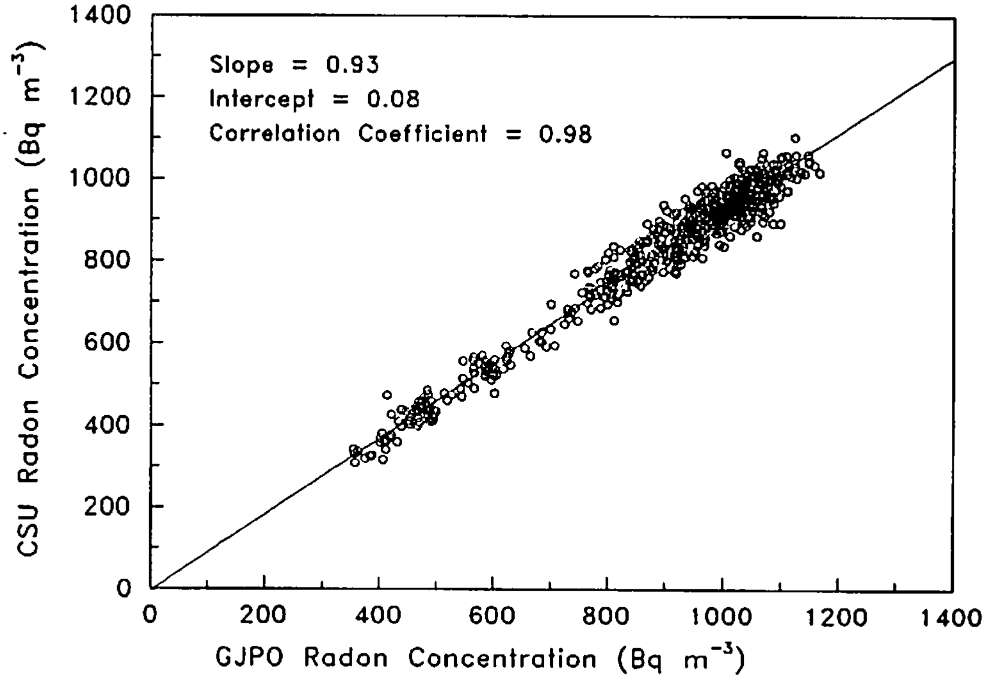

Fig. 5. Linear regression of CSU indoor radon results on those from GJPO.

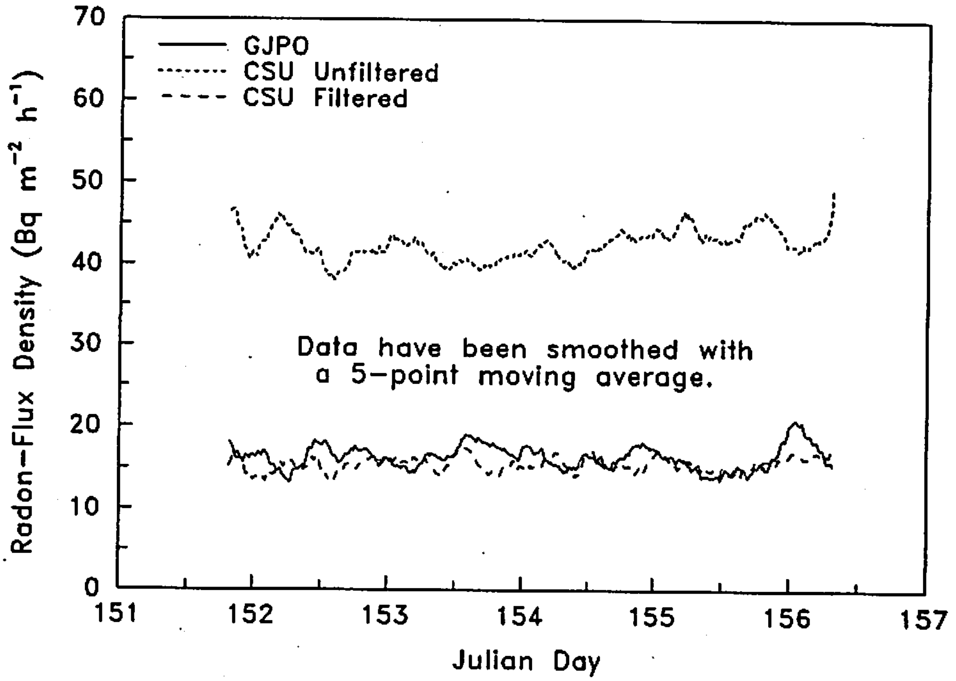

Fig. 6. Time plot of radon-flux density measurement results from the GJPO apparatus and the CSU apparatus with, and without, the thoron filter.

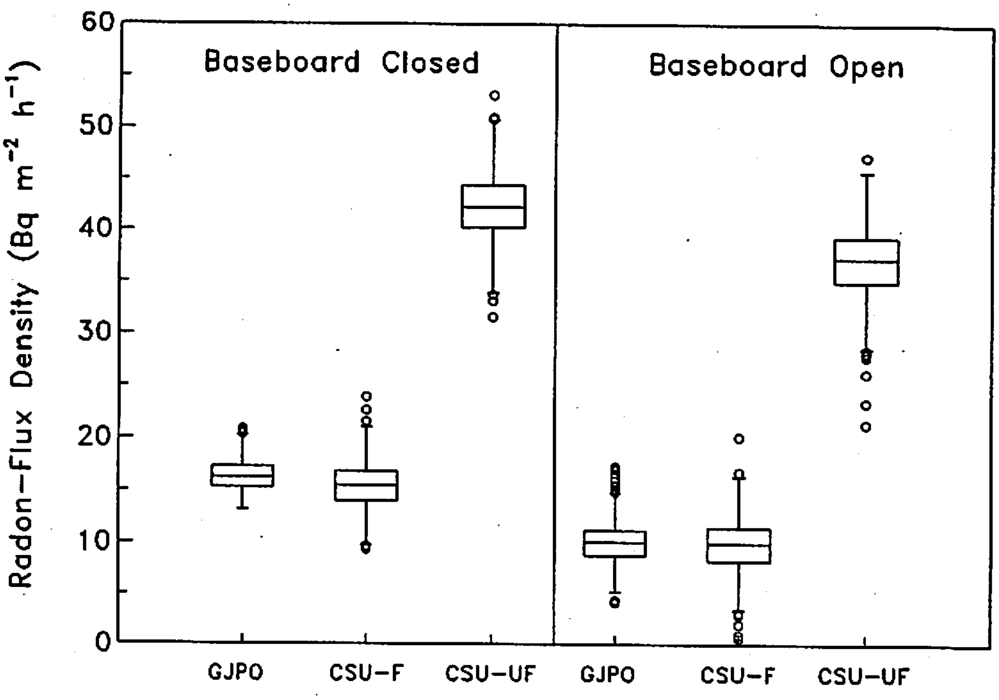

Fig. 7. Box-and-whisker plot showing typical intercomparison results. CSU-F are results with the thoron filter; CSU-UF are results without the thoron filter.