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In hilly limestone terrains of the southern Appalachians, subterranean networks of solution cavities and fissures present circulatory systems facilitating convective and advective transport of radon-bearing gas. Evidence suggests that the primary driving forces for transport are aerostatic pressure differentials created by the difference between the underground and the outside air temperatures. Examples are presented of houses experiencing elevated indoor radon levels as a consequence of communicating with such subsurface transportation systems. The location of a house near the upper or lower end of a subterranean-circulatory system seems to produce amplification of indoor radon levels in winter or summer, respectively.

INTRODUCTION

These studies of radon transport have their origin in an earlier finding that in Oak Ridge, Tennessee, houses built on limestone ridges had generally higher indoor levels of radon than houses situated in valleys (1). Subsequent investigations revealed that in similar limestone regions at Huntsville, Alabama, indoor radon levels can be substantially higher during the summer than during the winter (2,3). The transport mechanism for radon-bearing air in karst and its impact on indoor radon need better understanding, both in regard to evaluating the geographical prevalence of the phenomenon and the induced spatial and temporal effects that are possible.

This paper reports field studies made at houses in karst regions at Oak Ridge, Tennessee, and Huntsville, Alabama. A primary radon-transport mechanism is advocated of ascending or descending subsurface columns of air whose flows are largely driven by aerostatic pressure gradients created by the inground-outdoor air temperature differentials. The concept being proposed is similar to a topographical and temperature differential induced circulation of air advanced recently by Weekes (4). Weekes was attempting to explain the seasonally related intake or exhaust of air from wells located in the highly fractured rock on top of Yucca Mountain, Nevada.

LOCATIONS AND METHODS

The studies were conducted on the properties of two houses at each of which there were thin layers of clay surface soil underlain by karst. One was a crawlspace house located in Huntsville while the other was a basement, slab-on-grade house situated in Oak Ridge.

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Within the garden and lawn of the Huntsville house there were several openings connecting to solution cavities in the karst bedrock. This particular house had received radon-mitigation treatment prior to most of the measurements described in this paper. Continuous operation of the mitigation system precluded attempts to correlate changes in indoor radon with radon in the karst solution cavities. Instead, radon was measured inside three emergent solution cavities and inside a 1 m-deep, gravel-filled and clay-capped pit situated about 8 m distance from the largest solution cavity opening (hole 1). The latter was intended to simulate the ground immediately beneath the crawlspace and through which radon would have to pass before entering the basement of the house. Toward the end of the study, a 10 cm (3 inch) diameter pipe was inserted into hole 1; air-stream velocity was measured within the laminar flow of air.

The Oak Ridge house was situated on a hillside about 100 m from a cave whose entrance was a vertical distance of about 15 m below the house. Radon was measured in the basement of the house and within the cave. Radon mitigation has yet to be conducted in this house. Radon and temperature measurements were made inside the Oak Ridge house and the cave.

Radon measurements were made with flow-through scintillation cells, Wrenn chambers and Lucas cells. Scintillation cells and Wrenn chambers were operated automatically. Air samples were drawn into the scintillation cells through sampling lines. These cells were flushed periodically with outdoor air. Several meteorological parameters were also measured at each site. The nature of these measurements are tabulated in Table 1.

Table 1. Description of Field Measurements

	Site	Type	Frequency
Huntsville site	4 solution cavities	radon/grab samples, Lucas cell	occasional monthly
	3 solution cavities	radon/flow-through scintillation cell	each 8 hr
	1 gravel pit	radon/flow-through scintillation cell	each 8 hr
	1 solution cavity (hole 1)	air flow/ananometer	each 12 min
	backyard	meteorological	each 30 min
Oak Ridge site	cave	radon/flow-through scintillation cell	each 40 min
	cave	temperature	each 30 min
	house basement	radon/Wrenn chamber	each 30 min
	house basement	temperature	each 30 min
	backyard	meteorological	each 30 min

RESULTS AND DISCUSSION

HUNTSVILLE HOUSE

The results of radon concentrations in grab samples of air taken from inside four emergent solution cavities are depicted in Fig. 1. Concentrations of radon measured over a two year period were markedly elevated during warmer months of the year. During the seasonal cycling, the radon concentration reached as high as 300,000 Bq m^{-3}. Venting of radon occurs more strongly when the mean daily outdoor exceeds 15°C.

More finely time-resolved issuance of radon from hole 1 is shown in Fig. 2 during the seasonal transition month of October in 1988. During this month there were a number of acute radon venting events; during the two major ventings, radon was communicating, either directly or indirectly, to the air in the pit with an apparent lag time of about eight hours. The rate of movement of radon, if transporting by a straight-line route, would be about 1 m/hr. The strength of radon flow from hole 1 early in 1989 is depicted in Fig. 3. Radon-bearing air of up to 40,000 Bq m^{-3} was issuing at a few cm per second. If all of this air had been entering an overlying single-story house of typical floor size (170 m^2), the indoor radon level would be raised by about 150 Bq m^{-3}. Prior to the house on this site being mitigated, and during the winter, the indoor radon level was coincidentally averaging about 150 Bq m^{-3}.

At the Oak Ridge site, matched in-house and cave measurements of radon and temperature are shown in Fig. 4 for the month of October 1989. The radon levels are to a large degree anticorrelated. In particular, when the temperature of the cave air drops below 15°C, radon is flushed out of the cave. Presumably the flushing is produced by cooler, denser outside air entering through the cave entrance. Coincidentally, the radon concentration rises dramatically in the basement of the house.

These field studies in Huntsville and Oak Ridge show dramatic short-term and seasonal variations in radon concentrations within both the karst bedrock and within the overlying houses (2,3). Radon is apparently transporting through networks of solution cavities and communicating to the interiors of overlying houses. Such events imply radon transporting rapidly over distances considerably greater than the 1 or 2 m predicted by diffusion and soil-gas flow mechanisms controlling transport in low permeability soils adjacent to most houses in the U.S. (5).

One is left to account for the observations of radon being elevated during summertime (warm weather events) at the Huntsville house and during wintertime (cold weather events) at the Oak Ridge house. A still speculative mechanism based on geology and topologically different sitings is proposed to account for the observed differences. The two types of settings are shown schematically in Fig. 5. A network of solution cavities within limestone hills is present at both sites. It is proposed that in Huntsville, the house is situated at the lower end of a subsurface circulatory system whereas in Oak Ridge, the house is located above a circulatory system which contains an open cave as the principal entry point for outside air. It still remains to locate the uphill entry points in Huntsville, should such entry points indeed exist.

In summer, warm air may enter the upper end of the circulating system, increase in density as it cools and then sink downward. One would then expect to measure cool, radon-rich air exhausting from the bottom of the circulatory system of solution cavities. Just the reverse should happen in winter. Where a house is located on a hill with respect to a network of underground fissures or cavities should determine whether it will potentially experience amplified indoor levels of radon in warm or cold weather. Another prerequisite is that the subterranean network of channels should have openings to the outside air at both its upper and lower ends. Aerostatic pressure differentials created by temperature differences between inground and outside air can then develop to produce convective and advective movements of underground air. A very similar topographic mechanism for long-range transport of air in fractured rock has been proposed by Weekes (4) and modeled with partial success.

CONCLUSION AND RECOMMENDATIONS

Within hilly karst terrains of the southern Appalachians, a major subterranean transport pathway has been identified for moving radon. Circulatory systems of fissures and solution cavities in the limestone bedrock facilitate convective and advective transport of radon-bearing gas that can be communicated to houses built on these terrains. Seasonal amplifications in indoor radon levels have been observed. It is hypothesized that the location of a house at either the upper or lower end of a circulatory system is a primary factor in determining whether indoor radon is elevated in summer or winter. Further identification of air entry and exit points in the karst and geophysical, meteorological and tracer gas studies are needed to shed more light on these radon transport processes.

These results have important implications. For example, summer not winter may be the most appropriate season of the year for making screening measurements to determine whether or not a house has a radon problem. The effects of localized inhomogeneities in underlying bedrock may also be influential in explaining why neighboring houses often have very different indoor radon levels, even when their structures are similar.

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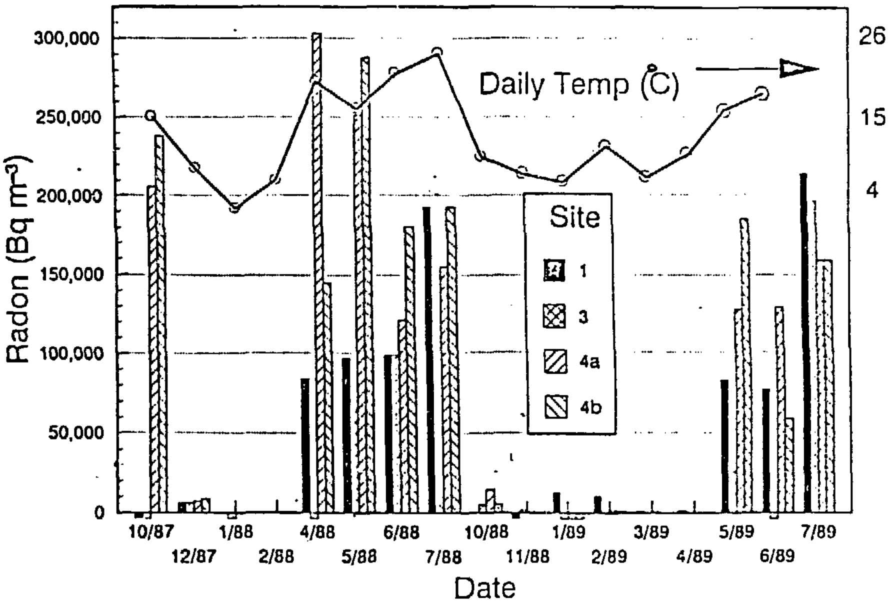


Fig. 1. Grab samples measurements by Lucas cell of radon in air from four holes in the backyard of House 11; negative values indicate that no measurement was made at a particular hole. The mean daily outdoor temperature is indicated for days that the holes were sampled.

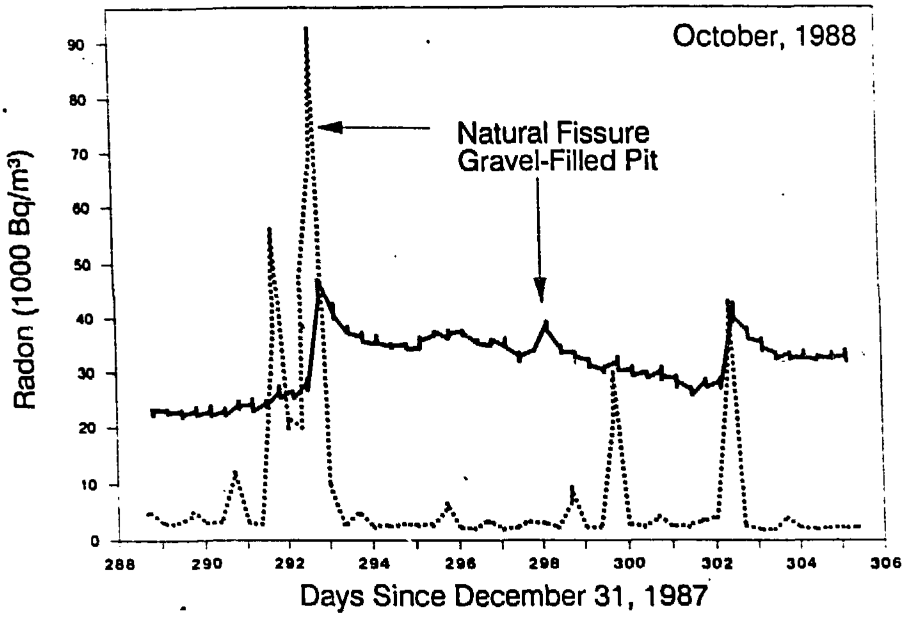


Fig. 2. Radon issuing from natural hole 1 and within a 1 m deep, gravel-filled, clay-capped pit, 8 m distance from the hole.

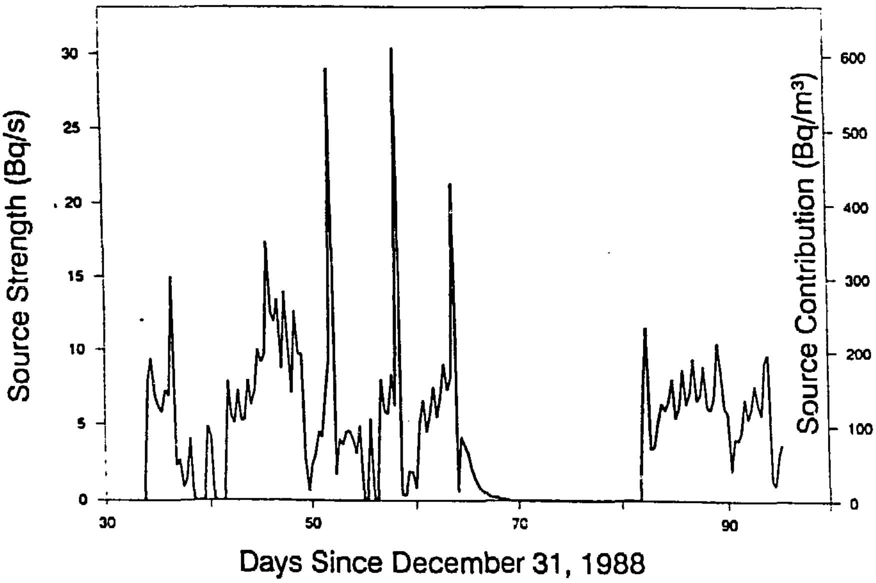


Fig. 3. Strength of radon venting from hole 1 and equivalent incremental radon concentration in 170 m², single-level house.

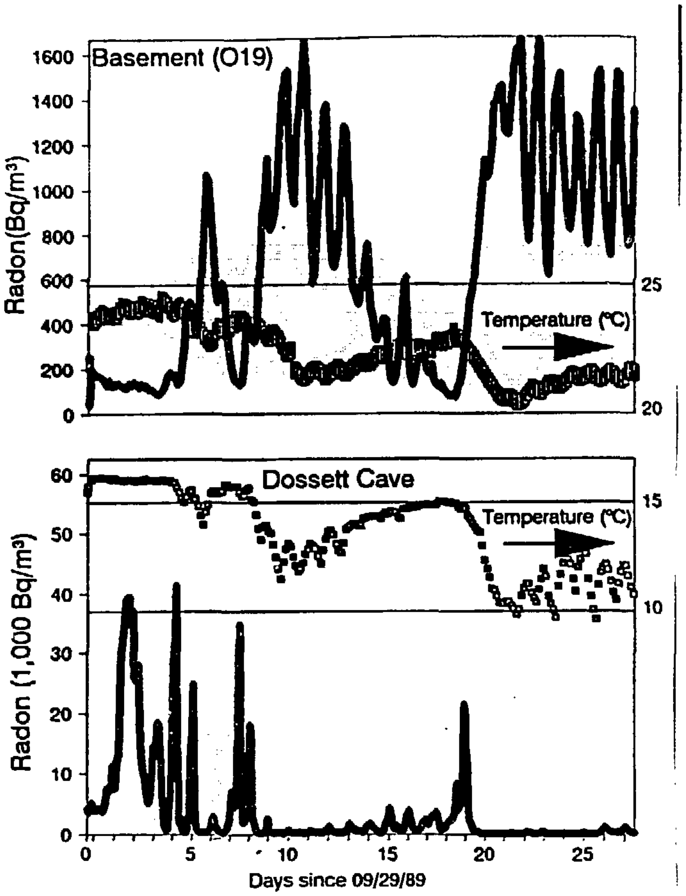
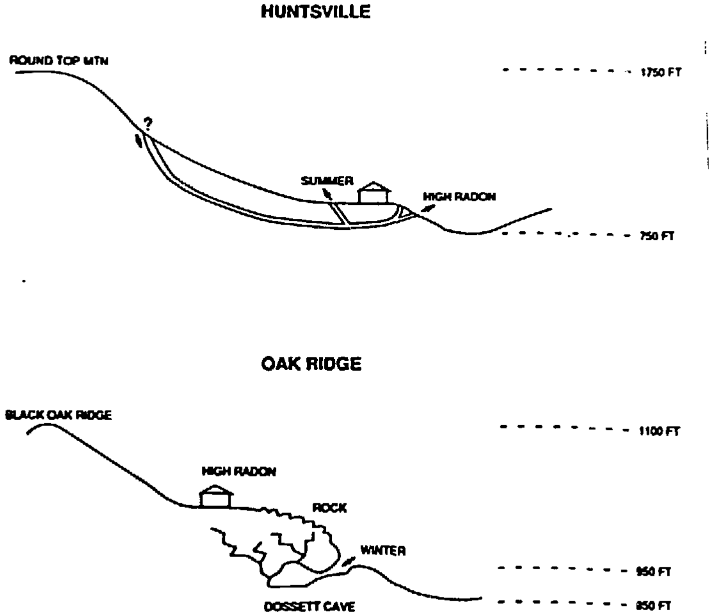


Fig. 4. Radon concentrations and temperatures inside a house and a closeby limestone cave.



Air Currents in Subterranean Cavity Networks
Control Radon Transport Differently in Huntsville and Oak Ridge

Fig. 5. Schematic of hillside locations, houses, and solution cavity systems in Huntsville and Oak Ridge.