# ALABAMA KARST VARIABILITY STUDY

James L. McNees, CHP and Susan H. Roberts
Alabama Radon Program

## EXECUTIVE SUMMARY

During 2004 the Alabama Radon Program conducted a year-long survey utilizing volunteer participants for monthly, quarterly and year-long indoor radon testing in Alabama residences. Participants were mailed radon kits which they utilized to conduct the measurements. Test results were charted and compared to the mean outside temperature as well as the maximum change in ground elevation within one-quarter mile of each residence. The study failed to substantiate the anticipated relationship between relative changes in ground elevation near the participating residences and the relative magnitude of the seasonal variation in indoor radon concentration. No significant correlation between adjacent terrain slope and increased seasonal variability was observed. The study did reveal that a significant fraction of Alabama residences located in karst geology had sufficient radon in the winter heating season to necessitate installation of a radon mitigation system, yet when tested during the summer air conditioning season, little or no excessive radon was be detected.

## INTRODUCTION

Beginning with the FY 2001 grant year, EPA Region IV imposed “Special Karst Conditions” on three of its states’ SIRG grants: Alabama, Tennessee, and Kentucky.[1] A modified version of those karst conditions has been in effect in these states since October 1, 2000 and continue to be in effect today. This grant condition requires the state radon programs to utilize special guidance for testing homes in karst areas. These karst areas are to be defined by each of the state programs with input from their state geologists. The authors believed that definitive studies consisting of same-house different-season test data should be performed to establish whether special guidelines need to be enforced, and if used, which areas in Alabama should be defined as karst.

The Geological Survey of Alabama previously identified zip code areas in Alabama that are underlaid by 75% or greater carbonate rock.[2] These areas were utilized as the “Potential Karst Area” zip codes described in the *Final Report; Outcomes from the Workshop on Measuring Radon in Karst Geology*, May 6-7, 1999. The single short-term test per house data in Appendix A of that document shows: (1) that both the arithmetic and geometric means for the measured radon concentrations are greater in the potential karst areas than for non-karst areas; (2) that the ratio of the arithmetic and geometric means from winter to summer are greater for potential karst areas than for non-karst areas; and, (3) that both the arithmetic and geometric standard deviations in each of the four seasons are slightly greater in the potential karst areas.[3] The Alabama Radon Program has designated these same zip code areas as its karst areas, however, they questioned whether the single test per house data conclusively proves that seasonal variations exist in sufficient frequency and of sufficient magnitude to warrant that all karst areas be subjected to the use of special karst guidance. This study was initiated to resolve those issues.

In any given house there are many variables affecting the result of a short-term radon measurement. These include house foundation type, age of the house, and house construction, as well as the extent of connection to karst solution cavities, and the magnitude of soil gas pressure beneath the house. We know that susceptibility to elevated indoor radon varies with type of foundation utilized and that different types of foundations predominate in different areas.[4] These differences, as well as the different lifestyles of the occupants, produce differences in radon measurements.

An increase in the arithmetic or geometric standard deviation from one area to another means that the combination of all the factors results in an increased variation in one area compared to another. It cannot separate out which factor or factors vary from season to season, nor can it discern the expected magnitude of the seasonal variation of any one factor. For that reason, Alabama chose to do a same-house different-season study as opposed to analyzing data consisting of a single short-term test per house.

The extent to which a house exhibits a temporal karst effect, or seasonal variation, would be dependent upon: (1) The extent to which the house is connected to solution cavities; (2) The extent to which the seasonal heating and cooling causes the existence of, or lack of, an internal stack effect within the house that would cause the house to draw air from below, and (3) The extent to which the difference between soil temperature and ambient temperature produces a seasonal gradient in the soil gas pressure exerted upon the house. If the latter is likened to the stack effect within the changes in elevation adjacent to the house, then, since the pressure gradient within a stack is directly proportional to the stack height, the pressure gradient of soil gas within the karst formations would then be directly related to the soil's stack height. The soil "stack height" is essentially the relative change in elevation in the vicinity of the house. Thus the seasonal variation of soil gas pressure would be related to *both* changes in temperature *and* the change in elevation in the vicinity of each individual house. If it is further assumed that the seasonal variation in indoor radon is related to the variation in soil gas pressure, then the seasonal variation in indoor radon would be related to *both* changes in temperature *and* the change in elevation in the vicinity of each individual house. Thus the study attempted to correlate seasonal variation among monthly tests within the same house to the change in elevation in the vicinity of that house.

## METHODOLOGY OF THE STUDY

### APPLICANT SOLICITATION

A letter describing the project and an application to participate was sent to 425 homeowners who had previously called the State Radon Hotline requesting information on radon and/or radon testing. From that solicitation, 84 homeowners signed the application or Agreement to Participate forms. From those 84, 65 participants were selected and sent acceptance letters. The 19 whose applications were rejected were sent a coupon for a free short-term radon test. Fifty-five of the initial 65 lived in areas identified as karst geology, characterized by hills, valleys and rock outcroppings in the yards, with the remaining 10 from non-karst geology areas in the state.

## CONDUCTING THE TESTS

The study's measurements were performed by the homeowners since the majority of indoor radon tests in Alabama are performed by homeowners and it is the seasonal variability in homeowner-conducted tests that the study is designed to determine. The error induced by the study's homeowners performing the tests are no more likely than errors from homeowner-performed tests whose seasonal variation the study is trying determine. The cost of having the investigator individually place and retrieve each individual test out-weighs the benefit of doing so.

The process began by obtaining quotes from certified laboratories to deliver the testing supplies directly to the study participants. AccuStar Labs was selected as the supplier and was provided with the names and addresses of the participants as well as a mailing schedule.

Beginning in January 2004, AccuStar sent each participant one short-term and two long-term test kits. One long-term test was for a full year test and one for the first three months. The short-term test was to be done during any two-day period of the month that was convenient to the homeowner; however, participants were asked to start the first quarterly test on or about Jan. 17 because this is, on average, the day having the coldest temperatures in north Alabama. (See Mean Outside Temperature section below.)

In each proceeding month, participants received another short-term test. In April, July, and October they also received another long-term test for each three-month period. For quality control purposes each month on a rotating basis seven of the 65 participants were sent duplicate short term test kits with instructions to use them as quality control duplicates of that month’s 48 hour test. In the first, second, and third quarters seven and in the fourth quarter 14 of the participants were sent duplicate long term kits to use as quality control duplicates for that quarter’s long term test. Thus 10.8% of both the short term and long term tests were requested to be made in duplicate.

Personal visits, as well as periodic reminder letters, were sent to participants to reinforce procedures, to clarify instructions and to encourage them to participate in the study as planned. The solicitation letter, the Agreement to Participate and each proceeding correspondence emphasized the need for all measurements to be made in the exact same location of the house, in the lowest lived-in level, and under closed-house conditions for the short-term tests and under normal house conditions during the remainder of the year including while the long term measurements were being taken. The only thing that was to change from one measurement to the next was the dates on which the measurements were made.

## VARIABLES AFFECTING TEST RESULTS

### Mean Outside Temperature

The investigators obtained the mean temperature for each day of the year from the closest reporting station to the test location, from internet web sites operated by the National Weather Service, www.srh.noaa.gov. The value for the daily mean temperature is plotted on the chart for each house.

### Adjacent Terrain Slope

Through personal visits, each house in the study was physically located and characterized. The latitude and longitude of each house was determined at a location near the front entrance utilizing a GPS locator. That latitude and longitude was entered into the web site, http://www.topozone.com/viewmaps.asp, resulting in a topographical map plotted on a USGS quadrangle map. A circle of a quarter-mile scale radius was drawn, centered on the location of the house. The maximum change in elevation from the house within a quarter-mile radius of the residence was determined. The Adjacent Terrain Slope (ATS) value assigned to that residence is one-tenth of the maximum change in elevation rounded to the nearest integer. For example: Test home #34 is located at 340° 44.297' North and 860° 43.833' West. The topographical map locates the residence at an elevation of 850 feet at the foot of Rainbow Mountain. The quarter-mile radius extends nearly to the top of Rainbow Mountain to an elevation of 1140 feet. The maximum change in elevation within the quarter-mile circle from the test residence is 290 feet. As shown in **Figure 1**, the ATS value for test home #34 is 29.

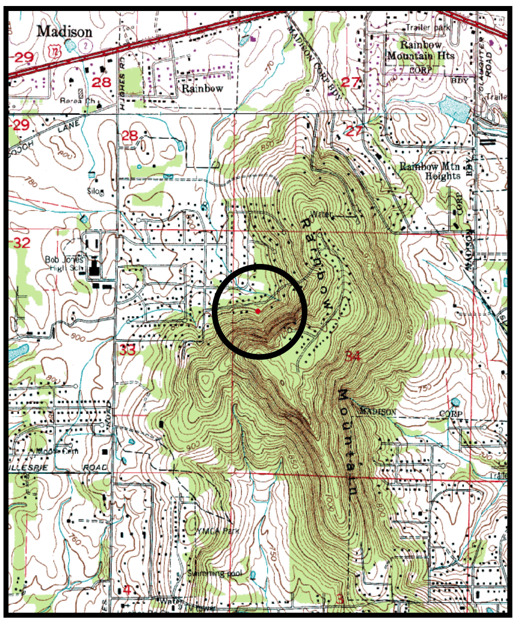


**Figure 1. The red dot in the center is the location of test house #34.**

### Location Characterization Code

Based upon on-site observations by the principle investigators and the topographical map location, each of the houses completing the Alabama Radon in Karst Variability Study was characterized as hilltop (H), valley (V), side of slope (S), or level terrain (L). This designation is known as the Location Characterization Code (LCC). An ATS value of 4 or less was characterized as level terrain.

## RESULTS

Fifty of the initial 65 participants conducted sufficient tests to provide chartable patterns. Forty-two from karst areas and eight from non-karst areas. **Table 1** shows the participation level of the volunteers.

| House # | Karst area | Results charted | Mitigation Decision | ST tests completed | Quarterly tests completed | Year-long tests completed |
|---|---|---|---|---|---|---|
| 1 | Y | Yes | Mit | 2 | 1 | |
| 2 | Y | Yes | No | 10 | 2 | Yes |
| 3 | Y | No | ISD | | | |
| 4 | Y | No | ISD | | | |
| 5 | Y | Yes | No | 7 | 1 | |
| 6 | Y | No | ISD | | | |
| 7 | Y | No | ISD | | | |
| 8 | Y | No | ISD | | | |
| 9 | Y | Yes | Mit | 4 | 1 | |
| 10 | Y | Yes | Mit | 5 | 1 | |
| 11 | Y | Yes | Mit | 6 | 2 | |
| 12 | Y | Yes | No | 10 | 2 | Yes |
| 13 | Y | Yes | No | 6 | 0 | |
| 14 | Y | Yes | No | 8 | 2 | |
| 15 | Y | Yes | No | 12 | 2 | Yes |
| 16 | Y | No | ISD | | | |
| 17 | Y | No | ISD | 2 | 0 | |
| 18 | Y | Yes | Mit | 6 | 0 | |
| 19 | Y | Yes | Mit | 6 | 3 | Yes |
| 20 | Y | Yes | No | 9 | 3 | Yes |
| 21 | Y | Yes | Mit | 8 | 2 | Yes |
| 22 | Y | Yes | Mit | 3 | 1 | Yes |
| 23 | Y | Yes | Mit | 10 | 2 | Yes |
| 24 | Y | Yes | ISD | 4 | 1 | |
| 25 | Y | Yes | Mit | 11 | 3 | Yes |
| 26 | Y | Yes | ISD | 5 | 0 | |
| 27 | Y | No | ISD | | | |
| 28 | Y | No | Mit | 7 | 2 | |
| 29 | Y | Yes | No | 7 | 2 | Yes |
| 30 | Y | Yes | No | 10 | 2 | Yes |
| 31 | Y | No | ISD | | | |
| 32 | Y | No | ISD | 1 | 1 | |
| 33 | Y | Yes | No | 5 | 2 | |
| 34 | Y | Yes | Mit | 7 | 3 | |
| 35 | Y | Yes | Mit | 9 | 3 | Yes |
| 36 | Y | No | ISD | | | |
| 37 | Y | Yes | Mit | 9 | 3 | Yes |
| 38 | Y | No | ISD | 4 | 0 | |
| 39 | Y | No | ISD | | | |
| 40 | Y | Yes | Mit | 10 | 2 | |
| 41 | Y | Yes | No | 4 | 2 | |
| 42 | Y | Yes | Mit | 12 | 2 | Yes |
| 43 | Y | Yes | No | 7 | 2 | Yes |
| 44 | Y | Yes | No | 9 | 2 | Yes |
| 45 | Y | Yes | No | 10 | 3 | Yes |
| 46 | Y | Yes | Mit | 10 | 2 | Yes |
| 47 | Y | Yes | Mit | 10 | 1 | Yes |
| 48 | Y | Yes | Mit | 8 | 3 | Yes |
| 49 | Y | Yes | Mit | 12 | 2 | Yes |
| 50 | Y | Yes | Mit | 9 | 3 | Yes |
| 51 | Y | Yes | Mit | 7 | 2 | Yes |
| 52 | Y | Yes | Mit | 12 | 3 | Yes |
| 53 | Y | Yes | Mit | 8 | 4 | Yes |
| 54 | Y | Yes | Mit | 10 | 3 | Yes |
| 55 | Y | Yes | No | 8 | 2 | Yes |
| 56 | N | Yes | Mit | 12 | 1 | Yes |
| 57 | N | No | No | 1 | 2 | Yes |
| 58 | N | Yes | Mit | 6 | 0 | |
| 59 | N | Yes | No | 11 | 4 | |
| 60 | N | Yes | Mit | 4 | 1 | |
| 61 | N | Yes | ISD | 5 | 1 | |
| 62 | N | Yes | No | 5 | 0 | Yes |
| 63 | N | Yes | No | 9 | 1 | |
| 64 | N | Yes | Mit | 10 | 0 | Yes |
| 65 | N | Yes | No | 11 | 3 | Yes |

**Table 1 shows the participation level of participants and those who completed year-long tests.**

### Madison County Karst Area

Twenty-three of the original 30 participants in Madison County completed sufficient tests for their results to be charted. Six (26%) had short-term radon tests consistently greater than 4 pCi/l as the seasons changed. Four (17%) tested consistently less than 4 pCi/l, and an astounding 13 (or 56%) of the 23 produced short-term radon tests both above *and* below 4 pCi/l.

Of the 13 homes exhibiting variable test results, four had highs less than 8 pCi/l and lows less than 4 pCi/l. The other nine, 39% of the Madison County houses charted in the study, had highs greater than 8 pCi/l and lows less than 4 pCi/l. Only three of the 13 (23%) that vary above and below 4.0 pCi/l appear to exhibit a seasonal pattern similar to the summer or valley karst effect characterized by increased radon in the summer. Ten (77%) exhibit the winter or hilltop karst effect characterized by increased radon in the winter.

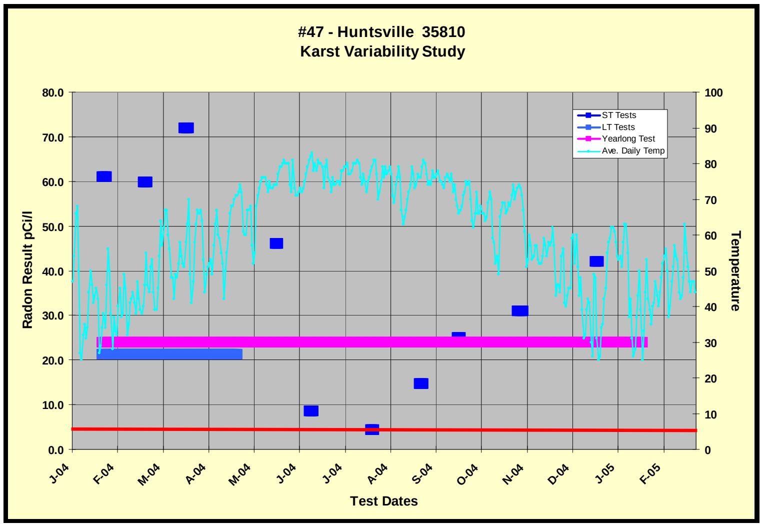


**Figure 2. House #47 tested 61 pCi/l in January, 59.8 in February, 72 pCi/l in March, but only 4.3 pCi/l in July.**

Three Madison County houses strongly exhibited the winter, or hilltop, karst effect. Short-term tests in house #49 ranged from 35 pCi/l in January to less than 4 pCi/l in the summer; house #40 ranged from over 73 pCi/l in February to below 4 pCi/l in the summer; house #47 **(Figure 2)** tested 61 pCi/l in January, 59.8 in February, 72 pCi/l in March but only 4.3 pCi/l in July.

### Florence, Sheffield, Muscle Shoals Karst Areas

Eighteen of the original 25 participants in the Northwest Alabama area of Florence, Sheffield, and Muscle Shoals completed sufficient tests for their results to be charted. Two (11%) had short-term radon tests consistently greater than 4 pCi/l as the seasons changed. Six (33%) tested consistently less than 4 pCi/l, and 10 of the 18 (56%) produced short-term radon tests both above and below 4 pCi/l.

Of the 10 Tri-Cities homes charted in the study having variable readings, four (22%) had cold weather readings greater than 20 pCi/l and summertime readings of less than 4 pCi/l. No summer or valley karst effect was observed in this area. This could be due to the fact that the Tri-Cites area of Northwest Alabama has a more level landscape than the Madison County area.

### Birmingham Non-karst Area

The results of eight houses in the non-karst area in Birmingham were charted. The terrain in the area of these tests is characterized by hills, ridges, and valleys with occasional rock out-croppings in the yards, similar in appearance to parts of Madison County utilized in the study except the Birmingham area is non-karst. Three of the eight homes had test results consistently less than 4 pCi/l. None of the eight non-karst area homes in the Birmingham area demonstrated the wide seasonal variations seen in some of the karst area homes.

### Invalidated Data and Participant

All data and the data chart for test house #28 was discarded because the homeowner stated that not all short term tests in her home were made in closed house condition. All tests in the house had been greater than 4.0 pCi/l and the homeowner dropped out of the study and had a mitigation system installed prior to the end of the year. Some of the tests for test houses #1 and

#61 were not utilized as those homeowners took it upon themselves to do some of their monthly tests on the floor above the lowest livable level where they had agreed to do all tests.

## Commonly Held Theory Did Not Predominate

The commonly held prevailing theory on variability in indoor radon concentrations in karst is that the principle contributing factor to seasonal variation is soil gases inside the karst cavities in the ridges and hills rises or falls depending upon the relationship between the constant ground temperature and ambient air temperature. Thus, in the wintertime the soil gas would rise in the ridges and hills, as shown in **Figure 3**. The constant year-round ground temperature in Cathedral Caverns near Huntsville is 58 degrees F. According to the theory, if the soil on which the house on top of the hill is connected to karst, then the radon in the house would be elevated in the winter and low in summer due to soil gas rising in winter and falling in summer. Further,

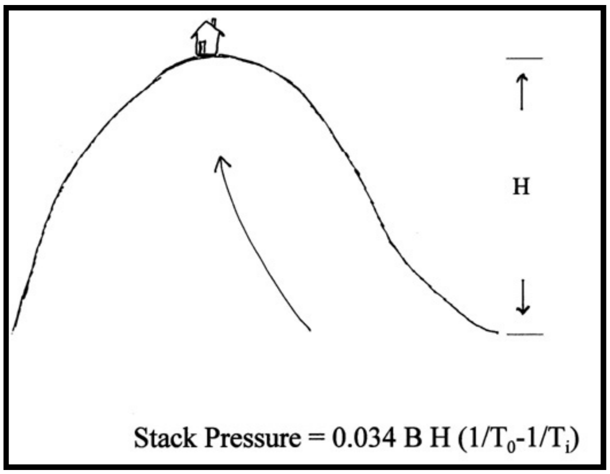


**Figure 3. Hilltop effect predicts elevated radon in winter as soil gases rise in the hill or ridge.**

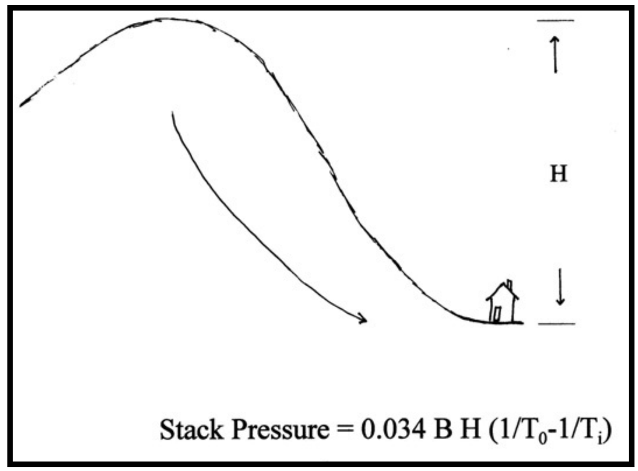


**Figure 4. Valley effect predicts elevated radon in summer as soil gases fall in the hill or ridge.**

if the rise of soil gas inside the ridge acts similar to hot gases rising in a stack, then the seasonal differential in soil gas pressure would be proportional to the change in elevation in the vicinity of the hill or ridge.

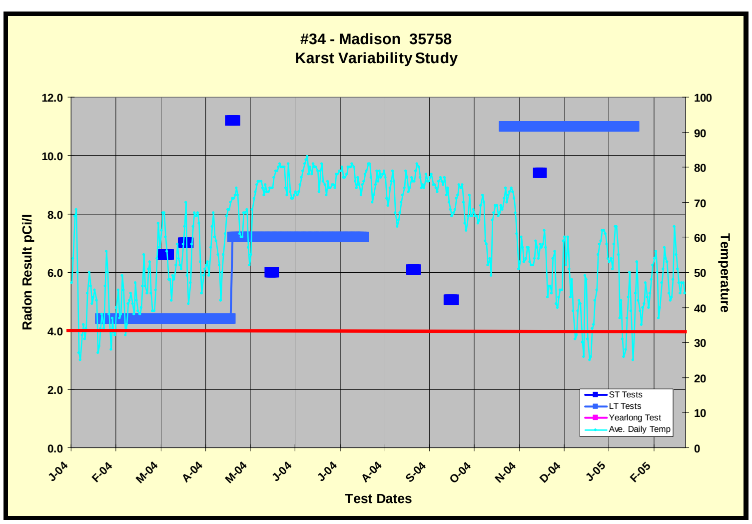


**Figure 5. Test house #34 predictably has the valley effect.**

Conversely, in the summertime, the commonly held prevailing theory is that soil gases inside the ridges and hills would fall because it would be cooler than the ambient outside air temperature, as shown in **Figure 4**. This would cause the radon concentration inside houses at the foot of the ridge and in the valleys to be elevated in the summer and low in the winter.

Seven of the karst area charted houses were characterized as being in a valley. Two of those valley homes exhibited the valley effect or elevated summer pattern, two of the valley homes exhibited the hilltop effect or elevated winter pattern, and three of the valley homes exhibited no obvious seasonal pattern. **Figure 5** is the chart for test house #34 whose topo was show above. This house exhibited the valley effect.

Test house #49 is located at the foot of Chapman Mountain on the edge of the valley and was characterized as a valley house. As seen in **Figure 6**, the topo map for this house, it is located similarly to test house #34. **Figure 7** displays the radon test results for this valley house. Apparently this valley house thinks it is on top of the hill.

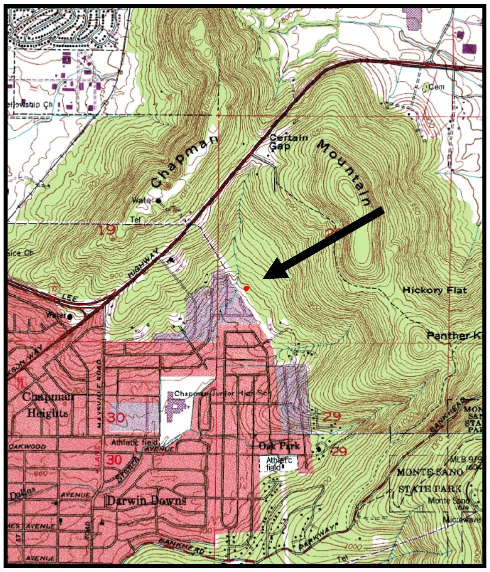


**Figure 6. Topo map of test house #49**

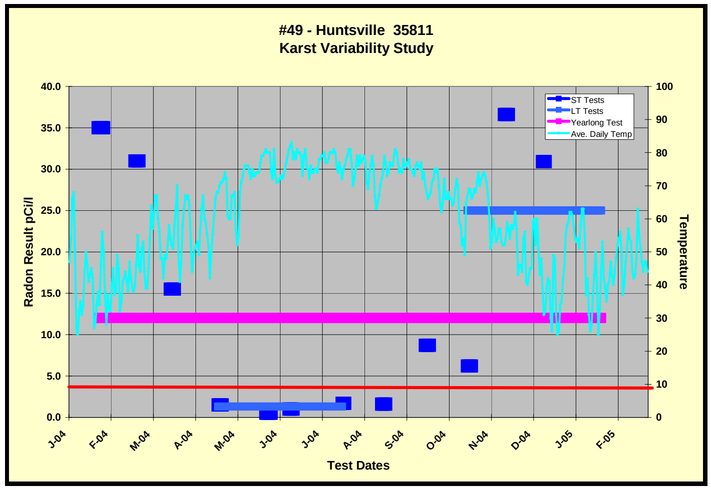


**Figure 7. Test house #49 is at the foot of Chapman Mountain, but thinks it is near the top as its radon measurements have the hilltop effect's pattern of elevated radon in winter.**

Sixteen of the karst area charted houses were characterized as being on the side of the slope in neither the valley nor the top of a hill or ridge. Ten of the 16 side of slope houses exhibited the hilltop effect of elevated radon in winter; five of the side of slope houses exhibited

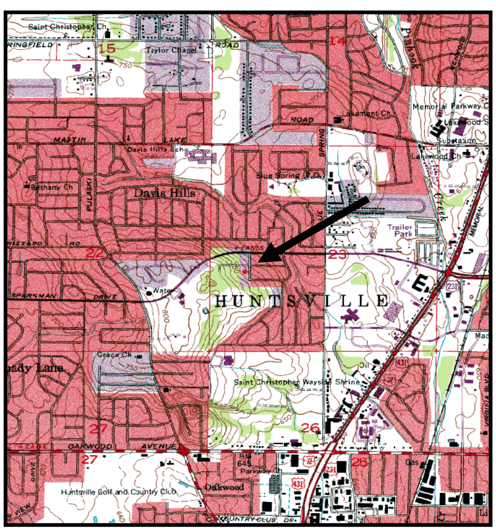


**Figure 8. Topo map of test house #50**

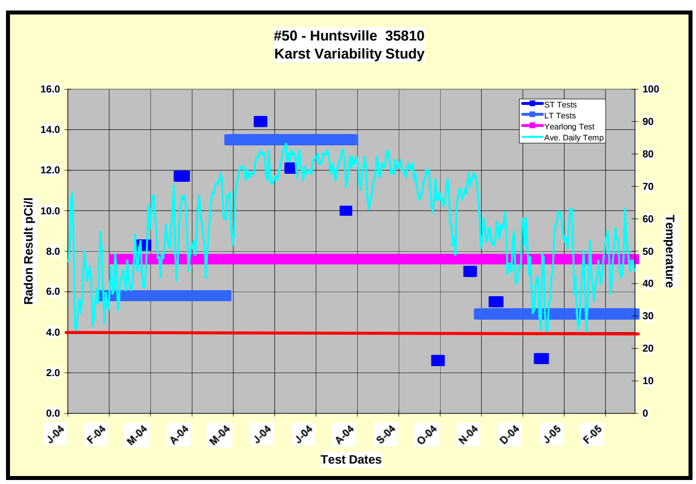


**Figure 9. Test house #50 is on the side of a slope, but thinks it is in the valley, by having the valley effect's pattern of elevated radon in summer.**

no obvious seasonal pattern; and one side of slope house, test house #50, is clearly on the side of a slope as shown in **Figure 8**, yet from the chart of its radon test results, shown in **Figure 9**, this house believes it is in the valley, as it clearly displays the elevated summer radon associated with the valley effect.

Ten of the karst area charted houses were characterized as being in an area of level ground. The commonly held prevailing theory on variability in indoor radon concentrations in karst would imply that on a widespread area of level terrain there will be minimal seasonal karst variability. However, only three of the 10 level terrain houses exhibited no obvious seasonal pattern, and seven of the 10 level terrain houses exhibited the hilltop effect of elevated radon in winter. For example, consider test house #42, which is characterized as on level terrain and having an ATS of 3, since in one-quarter mile in any direction only three contour lines are crossed on the topo map **(Figure 10)**. Test house #42's result chart **(Figure 11)** clearly exhibits the hilltop or elevated in winter pattern.

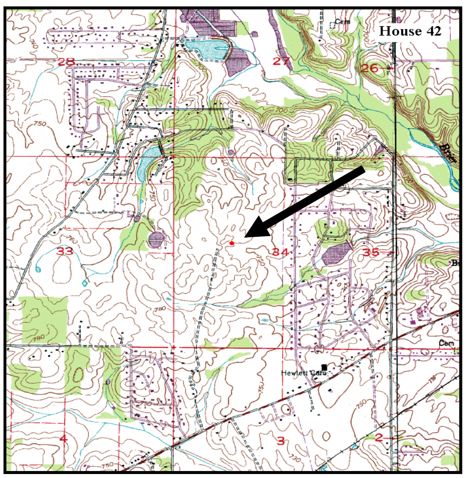


**Figure 10. The topo map for test house #42 indicates an ATS of 3.**

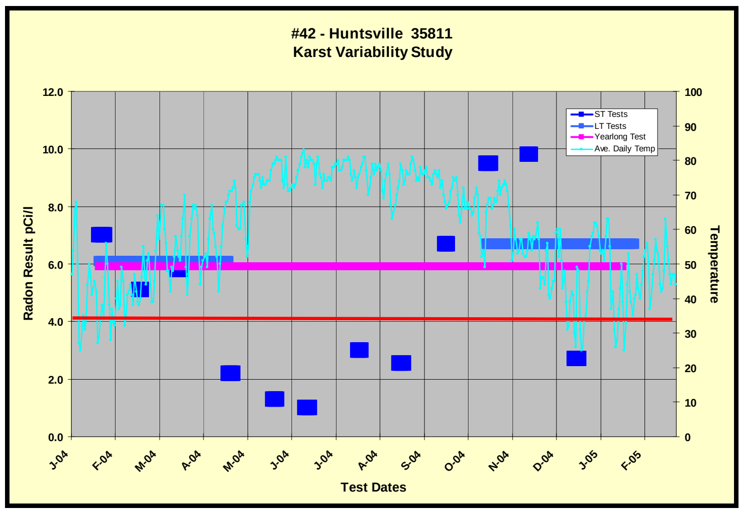


**Figure 11. Test house #42 is in a wide area of level terrain, yet it exhibits the hilltop or elevated winter pattern.**

## Adjacent Terrain Slope And Seasonal Variability

Each charted house was assigned an ATS value relative to the maximum change in elevation in any direction from the house. To examine the effect that the change in elevation adjacent to houses might have on the amount of seasonal variability in karst, a comparison was made of the relative or percent standard deviation of the monthly radon results for each house versus the ATS for each house. **Table 2** lists the values for all charted karst area houses having four or more valid monthly tests, with an average of monthly tests 2.0 pCi/l or greater. If change in terrain slope adjacent to the house was a significant factor in the magnitude of the seasonal variability, then the relative standard deviation of the monthly radon tests would show a dependence upon the ATS value.

| House # | Num St | St Ave | St Dev | % St Dev | ATS |
|---|---|---|---|---|---|
| 5 | 7 | 3.31 | 2.012 | 60.732 | 3 |
| 9 | 4 | 15.8 | 17.039 | 107.67 | 2 |
| 10 | 5 | 15.1 | 11.285 | 74.836 | 2 |
| 11 | 6 | 4.08 | 2.716 | 66.537 | 4 |
| 18 | 6 | 7.9 | 5.169 | 65.432 | 9 |
| 19 | 6 | 10.6 | 10.556 | 99.429 | 5 |
| 21 | 8 | 5.99 | 4.548 | 75.951 | 4 |
| 23 | 10 | 23.3 | 22.779 | 97.783 | 9 |
| 24 | 4 | 4.13 | 2.208 | 53.53 | 5 |
| 25 | 11 | 3.57 | 1.159 | 32.427 | 9 |
| 26 | 5 | 4.42 | 4.232 | 95.752 | 2 |
| 29 | 7 | 3.17 | 1.798 | 56.709 | 7 |
| 33 | 5 | 2.44 | 0.594 | 24.35 | 6 |
| 34 | 7 | 7.79 | 2.398 | 30.793 | 29 |
| 35 | 9 | 12.7 | 4.816 | 37.802 | 8 |
| 37 | 9 | 23.5 | 6.59 | 28.083 | 5 |
| 40 | 10 | 23.1 | 28.59 | 123.89 | 11 |
| 41 | 4 | 2.8 | 4.803 | 171.85 | 14 |
| 42 | 12 | 4.72 | 3.056 | 64.73 | 3 |
| 45 | 10 | 4.2 | 5.308 | 126.34 | 12 |
| 46 | 10 | 4.71 | 2.278 | 48.337 | 2 |
| 47 | 10 | 36.4 | 23.53 | 64.586 | 6 |
| 48 | 8 | 34.6 | 11 | 31.799 | 8 |
| 49 | 12 | 14.2 | 14.86 | 104.79 | 15 |
| 50 | 9 | 8.26 | 4.175 | 50.575 | 7 |
| 51 | 7 | 5.01 | 2.278 | 45.5 | 6 |
| 52 | 12 | 5.86 | 5.376 | 91.763 | 6 |
| 53 | 8 | 11.3 | 1.781 | 15.78 | 17 |
| 54 | 10 | 6.24 | 2.33 | 37.341 | 6 |
| 55 | 8 | 3.03 | 1.905 | 62.99 | 9 |

**Table 2. Data used to compare % St Deviation and ATS**

Using the values for ATS as the independent variable and the resulting relative standard deviation of the monthly reading within the house as the dependent variable the resulting plot, **Chart 1** was made to display the relationship between them. This reveals no correlation between ATS and seasonal variation.

The data points having the two greatest ATS values are (17,15.78) and (29,30.793). If they could be considered outliers, even though there is no known reason for them to be such, then the resulting **Chart 2** does show a weak relationship between changes in elevation adjacent to the houses and their seasonal variability in karst.

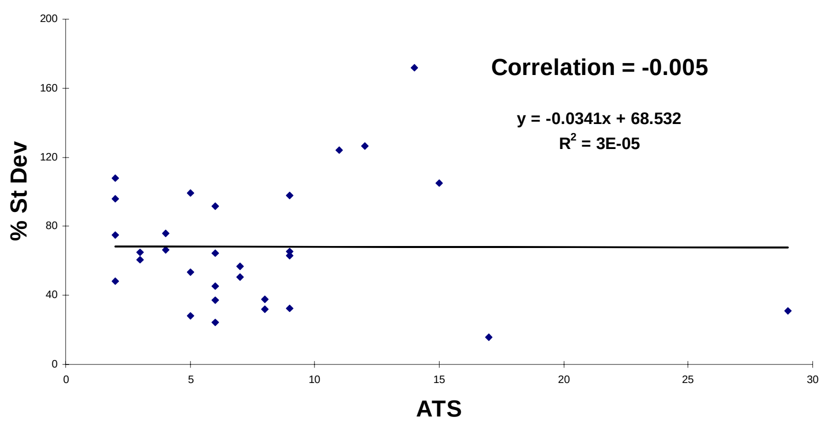


**Chart 1. Relationship of ATS and Percentage Standard Deviation of monthly test results within each test house.**

If the seasonal variability were primarily related to the gases rising and falling in the ridges and hills, and if the resulting pressure changes at the surface of the hills and ridges could be assumed to be analogous to that of height and temperature-related pressure changes in a stack, then the resulting pressure changes in soil gas at the surface under the houses would also be height related, i.e. related to the changes in elevation adjacent to the house.

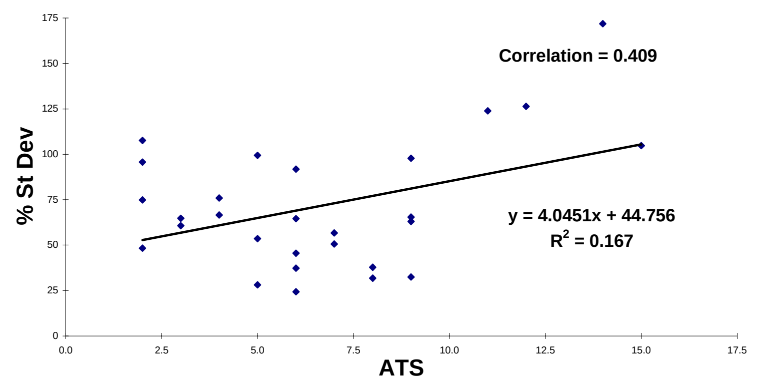


**Chart 2. Relationship of ATS and % St Dev without outliers.**

The lack of a stronger correlation between ATS and seasonal variability implies that seasonal rising and falling of soil gases in the hills and ridges is not the only principle factor in the observed seasonal variations in karst. This is further supported by the above observation that of the 10 karst area houses characterized as being on level terrain, three exhibited no seasonal pattern and seven exhibited the hilltop pattern of high radon in winter.

There is obviously an additional factor or factors equally or more important than the rising and falling of soil gases in varying elevations. The authors suggest the internal stack effect within the house itself during winter as another factor. Without documentation, it is assumed that the typical residence is maintained at a temperature in the vicinity of 70 degrees F. In north Alabama there is a significant heating season, wherein the outside temperature is consistently below the temperature within the residence. The internal stack effect within the house causes it to draw or pull in air from below during the winter. Conversely, north Alabama also has a significant cooling season wherein the outside temperature is consistently at or above the indoor temperature of the house. During this summer air conditioning season, there is a significantly diminished internal stack effect within the house, causing the house not to significantly draw in soil gas. Thus the houses on level terrain have less radon in summer than in winter.

There is increased seasonal variability in karst in part because the karst or other porous formations serve as the connection between the earth immediately below the house and the radon producing formation farther below. In summary, the house draws in soil gas in the winter and the karst formation simply serves as the straw through which the radon from below is drawn.

## Summertime False Negatives

Identification of summertime false negatives was not an initial objective of the study, however as the results developed, they emerged as the critical issue being identified. The authors defined "karst summer" to be from May 20 until September 24 because the average low temperature in north Alabama is greater than 58 degrees F during those days. The authors used 58 degrees F because that it is the constant ground temperature in Cathedral Caverns near Huntsville. The thinking was that seasonal variation in karst was due to rising and falling gas in the ridges due to the difference between ambient temperatures and constant ground temperatures.

Table 3 lists the 41 karst area homes charted, showing that:

- 27 had only negative radon tests in karst summer
- two that had no valid tests in summer are predicted negative due to the seasonal pattern displayed on their chart
- five had mixed results of both positive and negative tests in karst summer
- one with no valid summer test did not exhibit a pattern sufficient to predict the summer result
- only six of 41 or 14.6% tested above 4.0 pCi/l during karst summer

The Alabama database of known short-term radon tests currently has a greater than 4.0 pCi/l rate of 31.4% for Madison County, 34.6% for Colbert County, and 25.3% for Lauderdale County. Thus the karst area subject houses tested positive for radon during the summer at about half the rate of known short term tests for this part of the state.

| House # | Summer Test | Mitigation? | | House # | Summer Test | Mitigation? |
|---|---|---|---|---|---|---|
| 24 | Negative | ISD | | 1 | Negative | Mit |
| 52 | Negative | Mit | | 30 | Negative | No |
| 49 | Negative | Mit | | 23 | Negative | Mit |
| 55 | Negative | No | | 40 | Negative | Mit |
| 33 | Negative | No | | 26 | Negative | ISD |
| 44 | Negative | No | | 21 | Negative | Mit |
| 42 | Negative | Mit | | 9 | Predicted Neg | Mit |
| 51 | Negative | Mit | | 18 | Predicted Neg | Mit |
| 46 | Negative | Mit | | 29 | Mixed | No |
| 45 | Negative | No | | 25 | Mixed | Mit |
| 14 | Negative | No | | 54 | Mixed | Mit |
| 43 | Negative | No | | 10 | Mixed | Mit |
| 11 | Negative | Mit | | 47 | Mixed | Mit |
| 13 | Negative | No | | 22 | Unknown | Mit |
| 41 | Negative | No | | 34 | Positive | Mit |
| 5 | Negative | No | | 48 | Positive | Mit |
| 2 | Negative | No | | 35 | Positive | Mit |
| 19 | Negative | Mit | | 37 | Positive | Mit |
| 20 | Negative | No | | 50 | Positive | Mit |
| 12 | Negative | No | | 53 | Positive | Mit |
| 15 | Negative | No | | | | |

**Table 3. Summertime test results versus need to mitigate for the 41 karst homes charted.**

Twenty-nine houses tested negative or were predicted to test negative in the summertime as shown in **Table 3**. Fourteen did not need mitigation based upon the composite of all the tests done in the residence using a known or projected year-round average concentration of 4.0 pCi/l as the decision-making guideline. Two others had insufficient data to make a mitigation decision. More importantly, 13 of the 29 houses that tested negative for radon in the summertime were found to actually be in need of a mitigation system. **Thus, 45% of the summertime negatives were false negatives**.

Fifty-five karst area volunteers submitted signed agreements to participate in the study. Seven participants dropped out before completing a valid test. Also, as stated previously, data from test house #28, in which all test results had been greater than 4.0 pCi/l, was determined to be invalid.

Five of the six that did successfully complete one or more valid tests and dropped out early did so after receiving only results of less than 4.0 pCi/l. The authors believe that the homeowners who had one or more initial tests showing no radon problem were more apt to drop out than those with a significant amount of radon.

The 45% summertime false negative rate is thus believed to be an over estimation. If the five that dropped out after receiving initial negative results would have continued, and if they would have been proven to be true negatives, then 13 of 34 or 38% would be the rate of summertime false negatives. Further, the study was not a random sampling which, as previously noted, could bias the percentage of homes with a radon problem upward. Thus, the authors conservatively estimate that, until further research is done, one-third or 33% should be utilized as the approximate fraction of summertime negative radon tests in karst in Alabama that are false negatives.

Summertime false negatives is a very significant issue. More family relocations in Alabama occur in the summertime than in any other season. Real estate testing is believed to be the driving force in radon tests that lead to mitigations in Alabama and the main season for real estate transaction radon tests is not in the winter months. The authors estimate that when a family purchases an Alabama home during the summer located in a high radon karst area, and the radon test is negative, there will be approximately a one-in-three chance that the test was a false negative and that their new home will have a radon problem when cold weather arrives.

## LESSONS LEARNED AND OTHER FACTORS AFFECTING THE STUDY'S RESULTS

A monetary reward or other incentive may be needed to promote full and complete participation by participants. With no monetary reward for satisfactory completion of the project, the study is plagued with testing inconsistencies by some of the homeowner participants. Eleven of the original 65 participants dropped out during the first seven months of the study. A significant number of participants did not promptly perform the test when the kit was received, and some participants decided to use study test devices to test other floors and rooms rather than their agreed-to test location.

Full funding should be secured prior to starting the study. The study was hampered by an unexpected delay in receipt of funding from EPA Region IV, although we were assured that the approval for the project had been granted. Funding that was anticipated to arrive in May did not occur until mid-August. This gap in funds caused the program to be without funds for contacting and visiting participants for several months, which contributed to increased dropouts and inconsistent participation.

Study-specific instruction and data sheets should be enclosed with the test kits instead of the kit manufacturer's standard instructions. Confusion on the part of several participants concerning the placement and duration of the long-term tests could have been avoided had the state mailed out the kits to participants utilizing only instructions specifically prepared for the study.

Unexpected problems can occur. The vendor, AccuStar Labs, informed us that the third quarter alpha track long-term measurement devices mailed in mid-July did not pass their lab's quality control. Thus, there were no valid long-term quarterly measurements for that period. The participants were provided a year-long alpha track device which will capture the exposure for the third quarter as part of the full year.

## CONCLUSIONS

### Year-Long Testing Is Impractical

Sixty-five homeowners received the written description of what the study involved, then signed and returned a written statement agreeing to participate according to the procedure, which included a full-year long-term test. For 12 consecutive months, or until they dropped out, participants received one or more test kits in the mail. In addition, they each received three reminder letters during the year and at least one phone call. Of the original 65, only 32 successfully completed the year-long alpha track test. Thus, even with monthly reminders, the satisfactory completion rate for full-year alpha track tests by homeowners was less than 50%.

### Individual House Dynamics Significantly Influence Seasonal Patterns

In addition to the predictable temperature-driven movement of soil gases in the hills and ridges, undetermined dynamic factors within each house play a significant role. These dynamics cause houses to draw in radon in the winter heating season at a greater rate than in the summer air conditioning season. These dynamics work in combination and/or opposition with the underground flow of soil gases in the karst substrata to determine the resulting magnitude and pattern of seasonal variations in indoor radon concentration.

### The Predominating Variation Pattern Is Higher Radon During The Winter

The individual house heating versus air conditioning season dynamics is theorized to produce a seasonal pattern of elevated indoor radon in winter. The dynamics of soil gas movement in hills and ridges containing karst cavities is theorized to produce elevated indoor radon in the winter on the hill or ridge tops and elevated radon in summer in the valleys. The actual pattern is a combination of these influenced by the degree of connection between the house and the karst and between the karst and the radon source. The result is that in Alabama the seasonal pattern of elevated radon in winter occurs with significantly greater frequency and magnitude than elevated radon in summer.

**Steepness Of The Slope Of Terrain Adjacent To The Houses Was Not Significantly Correlated To Seasonal Variation**

The anticipated relationship of the maximum change in slope within a quarter-mile of each house and the relative magnitude of seasonal variation was not substantiated by the results. There are more factors influencing seasonal variability in karst than soil gases rising and falling in the hills and ridges, and the analogy of the karst cavities within the hills and ridges to that of a stack is an over simplification.

**Summertime False Negatives Are The Significant Issue**

The occurrence of summertime false negatives was found to be so significant that any report of the results of a summertime short-term radon test given to the current or future homeowner should contain a disclaimer and/or recommendation that the test be repeated during the heating season.

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