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# Multivariate Stepwise Regression Analysis of Indoor Radon Data From Ohio, U.S.A.

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**Abstract:** The indoor radon concentration in 125 houses was investigated in six 100 square kilometer areas in Ashtabula, Cuyahoga, Erie-Huron, Franklin, Pike, and Logan counties in the state of Ohio, U.S.A. All six study areas were located within the outcrop of the uraniferous rock formation known as the Ohio "black" Shale. For each house the thickness of the sediment overburden above the Ohio Shale was determined as were also numerous parameters relating to the design, construction, and maintenance of the house.

Multivariate stepwise regression analyses were performed with indoor radon concentration as the response variable, and the house and geological parameters as the predictor variables. The resulting regression equations are screening models that can be used to predict indoor radon levels. Of the several predictor variables included in the regression analyses, only two consistently made statistically significant contributions to the explanation of the variation in indoor radon. These variables are the penetration factor (a measure of the prevalence of radon entry points in the house substructure; higher values indicate more entry points) and the air exchange factor (a measure of the "tightness" of a house; higher values indicate greater indoor-outdoor air exchange). Increasing indoor radon levels were found to be associated with increasing penetration factor and decreasing air exchange factor.

**Key words:** Radon; stepwise regression; Ohio Shale.

## 1. Introduction

Radon-222 is a gaseous by-product of the radioactive decay of uranium-238, and is now known to be a major cause of lung cancer for people living in houses with elevated radon levels. Uranium occurs in at least trace amounts in all rocks, sediments, and soils. It has been estimated that, on average, the materials making up the continental crust contain from 2 to 3 ppm (parts per million) of uranium (Dyck (1978)). In areas where average crustal rocks are exposed at the surface, the amount of radon gas coming out of the ground is on the order of 0.1 to 0.5 pCi/l (picocuries per litre of air) outdoors and 1.0 to 1.5 pCi/l inside houses (Dyck (1978), Gessell (1983), and Nero (1988)). The background level for houses is well below the 4.0 pCi/l "action threshold" specified by the United States Environmental Protection Agency (EPA). For houses

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with average annual radon concentrations above the action threshold in the living areas, the EPA recommends that remedial work be done to reduce the concentration to below 4 pCi/l.

Of particular concern are those areas underlain by earth materials containing amounts of uranium significantly above the crustal average. Such materials are uncommon in most parts of the United States, but in Ohio they are fairly widespread as evidenced by the distribution of Ohio "black" Shale and glacial deposits (Figure 1). The geologic setting of Ohio,

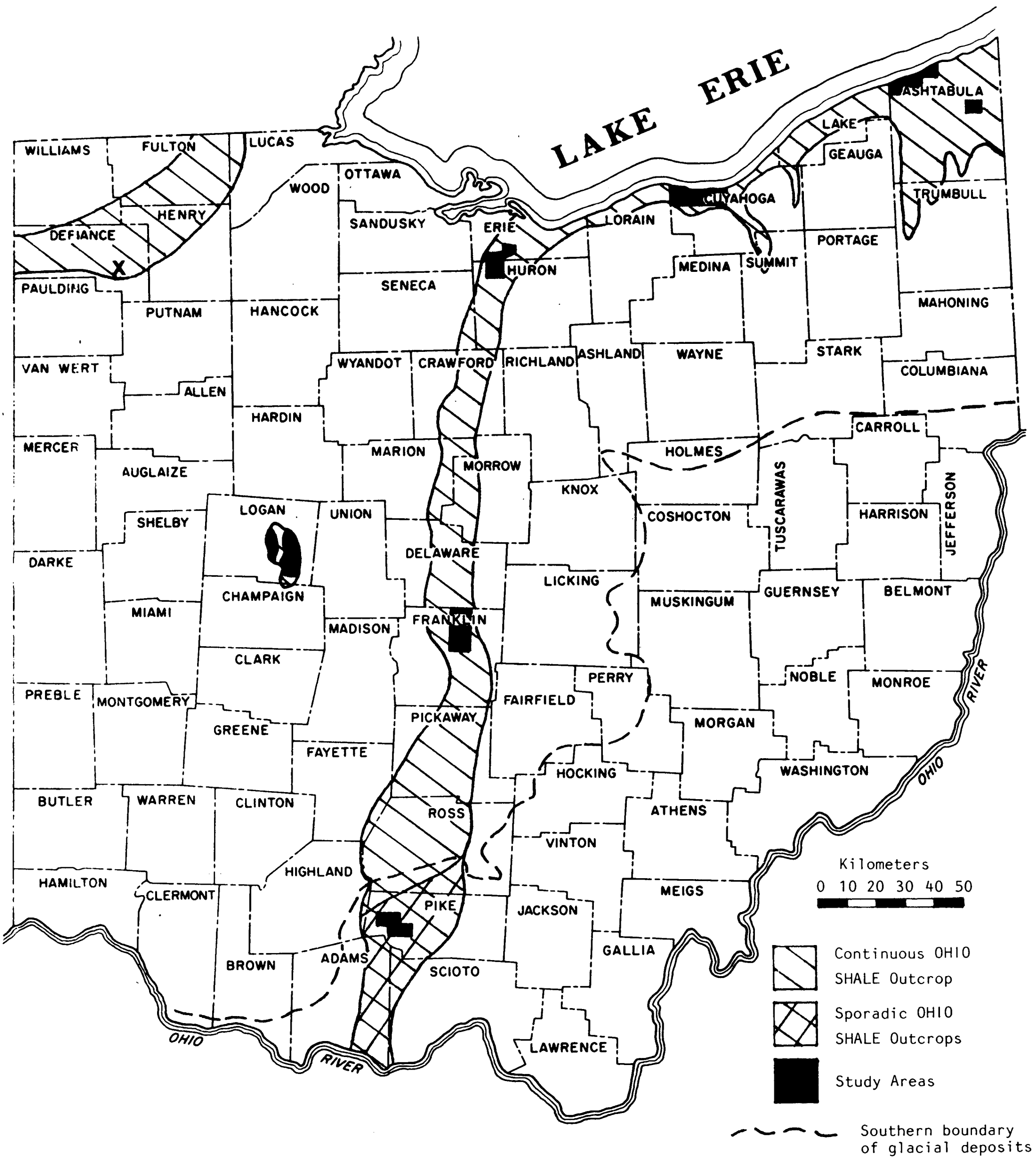


*Fig. 1. Locations of Ohio Shale outcrops and study areas, and distribution of glacial deposits (geology from Bownocker, 1947)*

insofar as uranium and radon are concerned, is very similar to that of Sweden with its Alum Shale and its glacial deposits (Akerblom (1986)).

The Ohio Shale is a geologic rock unit of upper Devonian age which is well known to be enriched in uranium. Uranium concentrations for this rock typically range between 10 and 40 ppm (Bates and Strahl (1958), Swanson (1960), Tracy (1983), Harrell and Kumar (1988)). The Ohio Shale underlies the entire eastern half of the state and also the extreme northwest corner (Majchszak and Honeycutt (1980a and 1980b)). However, it is only where the unit rises to the surface (the outcrop areas in Figure 1) that it poses a potential health threat. The short half-life of radon-222 (3.82 days) usually requires that the radon source material be less than 15 meters underground in order for significant amounts of the gas to survive the trip to the surface (Soonawala and Telford (1980), Tanner (1986)). It is important to recognize in this connection, that the Ohio Shale, in its areas of outcrop, is not everywhere exposed at the surface. In most places it is covered with up to 60 meters of river, lake, and/or glacial sediments (Soller (1986)). When the sediment overburden is thick, or is of low permeability, it acts as an effective barrier to the upward migration of radon from the Ohio Shale. However, in some parts of Ohio the overburden is itself enriched in uranium and thus can be a potent radon source. This is especially true of the glacial outwash, kame and esker gravel deposits (which consist, in part, of granitic rock fragments), and the glacial tills when they contain abundant fragments of the Ohio Shale.

In a recent study funded by the state of Ohio (Harrell and Kumar (1988)), we documented the factors affecting indoor radon levels in houses built on the Ohio Shale outcrop. The study was restricted to this geologic unit because it represents the single largest concentration of uranium in the state of Ohio. A literature review indicates that there has been no previous study of the radon hazards associated with the Ohio Shale. Although there have been some previous radon surveys in other parts of the state, none of these have included a sophisticated statistical analysis of the collected data.

The purpose of this paper is to present the results of a multivariate stepwise regression analysis of indoor radon concentrations (the dependent or response variable) and the associated house and geologic parameters (the independent or predictor variables). The resulting regression equations are, in effect, screening models that can be used to predict indoor radon levels from knowledge of the house design and construction, and the underlying geology. The data used in this statistical analysis come from Harrell and Kumar (1988).

## 2. Methods

Six study areas were selected within the Ohio Shale outcrop in Ashtabula, Cuyahoga, Erie-Huron, Franklin, Pike, and Logan counties (Figure 1). Each area was approximately 100 square kilometers, about the same size as the average Ohio township.

Potential houses for our study were selected in the field by a research assistant who contacted the residents and requested their participation. The only selection criteria were that the houses must be single family dwellings and they must, to the extent possible, be uniformly distributed across the study areas. The research assistant had no foreknowledge of the likely indoor radon levels, construction characteristics or underlying geology of the houses he selected. Of the 1150 households contacted, only 132 agreed to participate in our study. An additional 90 households in the six study areas later volunteered to participate as a result of local press coverage of our research, or were recruited by friends and family in the first group of selected houses. Of the 222 houses investigated, 125 were selected for the detailed statistical analysis reported on in this paper: i.e., those with basements where the radon detectors were both installed and retrieved by the research assistant. Our house sample is certainly not statistically random, but it is unbiased with respect to the geological and house parameters.

During the period of December 1987 through February 1988, a research assistant visited the participating houses in each study area for the purpose of installing charcoal-canister radon detectors in the basements. The winter months and basements were selected for indoor testing in order to both maximize and standardize the measured radon levels as recommended in the EPA protocol (EPA (1986)). These levels would be lower during other seasons when houses are more open and there is greater air exchange with the outside. The radon levels would also be lower in the upper stories both because radon tends to enter a house through the basement and because the air in basements has less opportunity to exchange with the outside than does the air in the upper levels of a house (Cohen and Gromicko (1988)). For each of the houses the homeowner, with the aid of our research assistant, filled in a questionnaire on the design and construction of their house with additional information requested on the family lifestyle and the prevailing meteorological conditions during the test period. Additionally, for each house, the thickness of the underlying sediment overburden was determined. It would, of course, have been desirable to measure the permeability of the overburden as well as uranium content of the Ohio Shale and overburden immediately beneath each house, but such determinations were not practical. Numerous samples of the Ohio Shale were collected in each study area but these were not necessarily from localities near the tested houses. They came from the accessible outcrop exposures. The uranium and radon contents of these rock samples were determined in order to establish the statewide variation in these parameters.

In the regression analyses for individual study areas, the observed indoor radon concentration serves as the response variable. However, when the data from all six study areas are combined into a single data set, a different measure of radon concentration is needed, one that removes as sources of variation the geological parameters not evaluated for each house. Whereas these parameters are fairly constant within a given study area, they vary widely among the areas. Without some kind of geographic correction, it would be possible to have identical houses with the same overburden thickness but with very different indoor radon levels because of differences in the other geological parameters. It is thus necessary to use a "standardized" radon concentration in the regression analysis when all study areas are combined. Standardization was accomplished by subtracting from the individual observed indoor radon concentrations the geometric mean of the indoor radon concentrations for the corresponding study area. Other standardization procedures were also tried. Regardless of the type of average used and whether it was subtracted or used as a divisor, the regression results were quite similar.

## 3. Influence of Geological and House Parameters on Indoor Radon Levels

The geological factors of Ohio Shale uranium content, and sediment overburden thickness and permeability, and perhaps also overburden uranium content are together the primary control on indoor radon levels in the six study areas. For the one geological parameter included in the present analysis, overburden thickness, it was found that indoor radon concentrations tended to decrease with increasing thickness when the other parameters did not vary.

Of secondary but still substantial importance are the physical characteristics of the houses themselves. It is a common occurrence in radon surveys to have houses with elevated radon levels in areas where there is no known or significant geologic source of radon. In such cases it seems likely that these houses, by virtue of their design, construction, and maintenance, tend to entrap and accumulate what little radon that might be coming up from the subsurface. These same engineering factors would also, of course, modulate indoor radon levels in areas with a strong radon source.

Data on the following parameters were obtained from the house questionnaire distributed to homeowners in this study. All of these parameters have been found, in one or more previous studies, to correlate strongly with indoor radon levels.

1. Penetration factor (dimensionless): a semiquantitative measure of the prevalence of entry points for radon gas (higher values indicate greater opportunity for radon penetration).
2. Air exchange factor (dimensionless): a semiquantitative measure of the "tightness" of a house (higher values indicate greater opportunity for exchange between indoor and outdoor air).
3. Temperature difference (in degrees Fahrenheit): average indoor temperature (the thermostat setting) minus average outdoor temperature (from the nearest meteorological or radio station) for the test period.
4. Age of house (in years).
5. Volume of basement.

Other semiquantitative and qualitative parameters are:

6. Condition of sump pump, if present
7. Condition of crawl space, if present
8. Frequency of use of fireplace, if present
9. Type of heating fuel used
10. Type of cooking fuel used
11. Number of people living in the house
12. Number of smokers living in the house.

These parameters did not vary systematically throughout the six study areas. Their standardization was thus deemed unnecessary.

All of these parameters were paired with indoor (basement) radon concentration in bivariate scatter plots and, where possible, in linear regression analyses. Only the first four parameters showed statistically significant correlations in one or more of the study areas (see Table 1). Increasing radon levels were found to be associated with increasing opportunity for gas penetration in the house substructure, decreasing opportunity for indoor-outdoor air exchange (i.e., increasing house tightness), and decreasing indoor-outdoor temperature difference (the smaller the difference, the less temperature-driven indoor-outdoor air exchange). The results for house age were contradictory. Of the four, only the penetration and air exchange factors had consistently high correlations with radon concentration. These findings are in agreement with many earlier studies (e.g., DOE (1986), Cohen and Gromicko (1988), and Nazaroff, Moed, and Sextro (1988)).

*Table 1. Bivariate linear correlations between indoor (basement) radon concentration and each of the variables used in the regression analyses*[1]

| Study area | Penetration factor (PF) | Air exchange factor (AE) | House age (HA) | Temperature difference (TD) | Overburden thickness (OT) | Number of houses | Other intercorrelations significant at the 95+% level[3] |
|---|---|---|---|---|---|---|---|
| Ashtabula Co. | 0.762 (99.9%)[2] | −0.800 (99.9%) | −0.490 (94.6%) | −0.846 (99.9%) | 0.068 (19.7%) | 16 | PF-HA, PF-TD, AE+HA, AE-PF, AE+TD, TD+HA, OT-HA |
| Cuyahoga Co. | 0.830 (99.9%) | −0.660 (99.9%) | −0.299 (85.4%) | −0.752 (99.9%) | 0.133 (47.5%) | 25 | PF-TD, AE-PF, AE+TD |
| Erie-Huron Co.'s | 0.710 (99.9%) | −0.715 (99.9%) | −0.236 (83.4%) | −0.437 (99.2%) | 0.433 (99.2%) | 36 | PF-TD, AE-PF, AE+TD |
| Franklin Co. | 0.747 (99.9%) | −0.712 (99.9%) | 0.607 (99.2%) | −0.679 (99.8%) | 0.001 (< 1%) | 18 | PF-TD, AE-PF, TD-HA |
| Pike Co. | 0.358 (61.7%) | −0.352 (60.8%) | −0.341 (59.2%) | 0.036 (6.7%) | 0.071[4] (12.1%) | 8 | none |
| Logan Co. | 0.395 (93.1%) | 0.053 (18.6%) | 0.211 (65.4%) | 0.232 (70.0%) | −0.243 (72.4%) | 22 | PF+HA |
| All study areas combined[5] | 0.461 (99.9%) | −0.315 (99.9%) | −0.076 (60.1%) | −0.071 (56.6%) | −0.019[6] (16.9%) | 125 | AE-PF, AE+TD, AE+HA, TD+HA, OT-HA |

[1] All correlations, except those in the rightmost column, are for indoor (basement) radon concentration and the variable identified by the column heading.
[2] Values in parentheses are the significance level of the associated bivariate linear correlation coefficient, $r$ (=[1-alpha probability] · 100; based on the $F$-test). A level of 95% or above is normally considered statistically significant.
[3] This column summarizes the bivariate linear correlations among the variables listed in the column headings. The variable abbreviations are separated by a "+" if the correlation is positive, and by "−" if negative.
[4] Based on 7 houses.
[5] Standardized indoor (basement) radon concentrations used (see Footnote 1 in Table 2).
[6] Based on 124 houses.

There is yet another house parameter, the "depressurization or stack effect," which may be the most important of all and which we were unable to measure in this study. House depressurization is caused by the exhausting of indoor air to the outside through fireplaces, wood stoves, combustion furnaces, clothes dryers, attic fans, and by normal leakage of heated air to the outside through the roof, walls, windows, and doors. The lost air must be replaced either by fresh air from the outside, or by soil air from beneath the house. It is usually the case that the "tighter" the house, the larger the proportion of soil air drawn in by the negative pressure conditions (Michel (1987)). Whenever possible, the depressurization effect should be evaluated by measuring the indoor and outdoor pressures during the radon testing period. The air exchange factor calculated in this study does, however, seem to provide some indication of the extent to which soil air will be drawn into a house by serving as a measure of tightness.

One would expect that the air exchange and penetration factors are closely related to the age of a house (assuming no extensive renovations were made since the house was built). Our survey results indicate that there is a tendency for the older houses to have both higher air exchange and higher penetration. The only statistically significant correlation between radon concentration and house age in Table 1 is for Franklin County where increasing radon is associated with increasing house age. Apparently, in this case, the effects of greater penetration dominate over those of greater air exchange. Because of the opposing effects of penetration and air exchange, one would not expect high or even consistently positive or negative correlations between radon concentration and house age. This is well illustrated in Table 1.

## 4. Screening Models and Regression Analyses

One of the primary objectives of our study (Harrell and Kumar (1988)) was to develop screening models that would allow us to predict the effects of geological and especially house parameters on indoor radon concentrations. The technique we used to derive these models is multivariate stepwise regression analysis with forward (rather than backward) stepping (see Draper and Smith (1981) p. 307–311 for details). In this technique, a response variable (radon concentration) is regressed, in a stepwise fashion, against a number of predictor variables (the house and geological parameters and various derived terms). The analysis begins with no predictor variable in the model. After the first step, the one predictor variable most highly correlated with radon is added to the model. In the next step, another variable is added. This is the one with the highest "partial" correlation with radon (i.e., the highest bivariate correlation after compensation for the interaction effects of the variable already in the model). At each step the statistical significance of the contribution of the added variable is evaluated with an $F$-test. Regardless of their partial correlation with radon, a variable cannot be added to the model if its contribution is not significant at the 95% (alpha = 0.05) level. An alternative outcome to adding a new variable at a given step is the removal of a variable already in the model. Variables can be removed if their contribution drops below the 95% significance level as a result of interactions among the variables in the model. Variables are either added or removed in subsequent steps until no further variables either pass (to enter) or fail (to leave) the $F$-test. The final model is both optimal and parsimonious in the sense that it contains only those vari-

*Table 2. Results of stepwise regression analyses (using full-quadratic models with all variables included)*

| Study area | Screening model (Final prediction equation)[1,2] | Correlation coefficient[3] | Variance explained[4] | Number of houses |
|---|---|---|---|---|
| Ashtabula Co. | $BR = 4.396 - (0.0939 \cdot TD) + (0.0554 \cdot PF^2)$ | 0.894 | 79.9% | 16 |
| Cuyahoga Co. | $BR = 8.558 + (0.543 \cdot PF^2) - (0.0867 \cdot AE \cdot PF) - (0.00469 \cdot TD^2)$ | 0.912 | 83.1% | 25 |
| Erie-Huron Co.'s | $BR = -24.621 + (0.0719 \cdot AE^2) + (37.576 \cdot PF) - (1.829 \cdot AE \cdot PF) - (0.0271 \cdot AE \cdot OT) + (0.244 \cdot PF \cdot OT)$ | 0.961 | 92.4% | 36 |
| Franklin Co. | $BR = 60.068 - (37.597 \cdot PF) + (7.718 \cdot PF^2) + (0.0165 \cdot HA) - (0.0191 \cdot AE \cdot HA) - (0.00972 \cdot AE \cdot TD)$ | 0.992 | 98.4% | 18 |
| Pike Co. | None (no significant relationship exists) | – | – | 8 |
| Logan Co. | $BR = 4.681 + (5.082 \cdot PF^2) + (0.00104 \cdot OT^2) - (0.165 \cdot PF \cdot OT)$ | 0.754 | 56.8% | 22 |
| All study areas combined | $BRs = 2.401 + (2.393 \cdot PF^2) - (0.344 \cdot PF \cdot AE)$ | 0.560 | 31.3% | 125 |

[1] BR = indoor (basement) radon concentration (pCi/l)
BRs = standardized indoor (basement) radon concentration (BR – geometric mean for each study area)
PF = penetration factor (dimensionless)
AE = air exchange factor (dimensionless)
HA = house age (years)
TD = temperature difference (indoor minus outside; °F)
OT = overburden thickness (feet)

[2] Stepwise regression with 'forward selection' was performed on full-quadratic models. Each model included the following 20 variables: PF, AE, HA, TD, OT; $PF^2$, $AE^2$, $HA^2$, $TD^2$, $OT^2$, and PF · AE, PF · HA, PF · TD, PF · OT, AE · HA, AE · TD, AE · OT, HA · TD, HA · OT, TD · OT. Only those variables making statistically significant contributions were included in the final prediction equation (i.e., those that passed an *F*-test at alpha = 0.05).

[3] Multiple correlation coefficient, *R*.

[4] Percent of the total variance in BR (or BRs) explained by the variables in the final prediction equation.

ables that make a significant contribution to the explanation of the variation in indoor radon concentration.

The predictor variables included in our regression analyses are the four house parameters most highly correlated with indoor radon (the air exchange and penetration factors, temperature difference, and house age) and overburden thickness (Table 1). Added to these parameters were fifteen "derived terms": i.e., each of the parameters squared and all possible pairwise cross-products of the parameters (see footnote 2 in Table 2). The value of the derived terms is that they make it possible to recognize and incorporate the effects of nonlinear relationships between radon concentration and the house and geological parameters, as well as interactions between intercorrelated parameters.

The results of the stepwise regression analyses are summarized in Table 2. Included in the table are the screening models for each study area and, using the standardized radon concentration, for all study areas combined. No screening model could be derived for Pike County because of the small number of houses with basements. It is noteworthy that the models for the other study areas always include the penetration factor and/or the air exchange factor. More importantly, these two parameters are the only ones included in the model for all areas combined. These results are not surprising given the high intercorrelations between radon and these parameters in Table 1.

The results also suggest that models with the penetration and air exchange factors alone might be nearly as good for prediction purposes as those in Table 2. Such models have an appeal not only because these parameters are of known fundamental importance, but also because they are easily and conveniently measured. Table 3 summarizes the results of this second series of stepwise regression analyses. The percentage of the total variances explained declined for these new models, but, with the exception of Logan County, they are still respectable.

## 5. Discussion

It can be seen in Tables 2 and 3 that many of the equations contain high order terms ($X^2$ and $X \cdot Y$) without the corresponding low order terms (X and Y). When the latter are absent it is, of course, because their contribution to the regression was not statistically significant. It is, however, conventional in other regression applications (e.g., bivariate curvilinear and trivariate trend surface analyses) to include low order terms even when they are not significant. It could be argued that this convention should be adopted in stepwise regression. We do not agree because, in our case at least, we were interested not only in developing empirical prediction equations but also in establishing the nature of the relationship between radon concentration and each of the predictor variables. Only the statistically most parsimonious equations will satisfy both objectives.

Although the terms included in Tables 2 and 3 supposedly make "statistically significant" contributions, it must be recognized that in most stepwise regression analyses (ours included) the actual probability levels are unknown because of unrecognized errors in the variables and violations of underlying assumptions to the *F*-test. This is not a matter of concern because stepwise regression analysis should be simply viewed as an objective procedure for "making a series of internal comparisons that will produce what appears to be the most useful set of predictors" (Draper and Smith (1981) p. 311–312).

*Table 3. Results of stepwise regression analyses (using full-quadratic models with only the air exchange and penetration factors)*

| Study area | Screening model (Final prediction equation)[1,2] | Correlation coefficient[3] | Variance explained[3] | Number of houses |
|---|---|---|---|---|
| Ashtabula Co. | $BR = 3.829 - (0.143 \cdot AE)$ | 0.800 | 64.0% | 16 |
| Cuyahoga Co. | $BR = 2.296 + (0.644 \cdot PF^2) - (0.0749 \cdot AE \cdot PF)$ | 0.886 | 78.5% | 25 |
| Erie-Huron Co.'s | $BR = 30.615 + (4.512 \cdot PF^2) - (1.077 \cdot AE \cdot PF)$ | 0.905 | 81.9% | 36 |
| Franklin Co. | $BR = -4.547 + (1.948 \cdot PF^2)$ | 0.782 | 61.2% | 18 |
| Pike Co. | None (no significant relationship exists) | — | — | 8 |
| Logan Co. | $BR = 1.949 + (1.436 \cdot PF^2)$ | 0.430 | 18.5% | 22 |

[1] See Footnote 1 in Table 2 for variable codes.
[2] See Footnote 2 in Table 2 regression procedure. Each model evaluated included the following 5 regression variables: PF, AE, $PF^2$, $AE^2$, and $PF \cdot AE$.
[3] See Footnotes 3–4 in Table 2.

## 6. Conclusions

The screening models produced by multivariate stepwise regression (Table 2) can be used to predict indoor radon levels in the six study areas, but the predictions would, at best, be only rough estimates. The model for all study areas combined explains relatively little of the total variance but it is more universal in its applicability. It can be used to estimate the "relative" radon concentrations for houses in any given localized area within the Ohio Shale outcrop (and not just in our study areas). As prediction equations, the current screening models are of limited value. More houses are needed to increase the accuracy of the models to an acceptable level.

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