# INSIGHTS INTO THE TIME-DEPENDENT BEHAVIOR OF INDOOR RADON LEVELS FROM CONTINUOUS MEASUREMENTS

R. H. Socolow, T. A. Reddy, and D. A. Hull
Center for Energy and Environmental Studies, Princeton University

A multi-year data base of continuous half-hourly measurements of indoor radon in three New Jersey homes, together with climatic and indoor environmental parameters, has been explored with the goal of identifying and quantifying the physical mechanisms which influence radon levels. Our studies have involved statistical analysis and linear regression of data at the weekly average level for three residences, at the daily level for two residences and at the half-hourly level for one residence. We confirm the importance of pressure-driven effects originating from indoor-outdoor temperature differences and from air-handler operation. In the case of half-hourly basement radon data during the fall, the statistical analysis suggests a physical system responsive to the ambient, basement and soil temperatures, where radon is pumped from the basement drains into the house during the night and removed through the drains during the day.

## INTRODUCTION

The Center for Energy and Environmental Studies of Princeton University has, over the last three years, built up a large data base of half-hourly average radon concentrations and other related parameters over several months for more than a dozen occupied residences in New Jersey (Dudney et al. 1988; Reddy et al. 1990). However, the present statistical investigation will be limited to three residences for which the data span almost an entire year. Since the database is continuous, and physically one does expect persistence effects over consecutive half hourly time intervals, a productive way to analyze the data is in a time-series framework.

This paper will briefly report the results of our analysis involving three time scales: variations over one year, seasonal variations and diurnal variations (Reddy et al. 1990; Hull 1990). Though the data are limited to a relatively small number of houses in only one climate, that of central New Jersey, the statistical results obtained do yield generalizable insights into how climatic and house parameters influence indoor radon levels.

## DESCRIPTION OF HOUSES AND DATA BASE

The three residences, PU-2, PU-21 and PU-22, show distinct and characteristic differences not only in their layout, construction and subslab conditions, but also in the air-handling equipment used for heating and cooling the house (HAC) (see Table 1). In the rare periods of time when these houses were unoccupied we performed intrusive experiments; otherwise, the houses were operated by the occupants themselves with minimum intrusion by the researchers.

The parameters continuously measured on a half-hourly time scale for all three houses and their associated symbols are listed in Table 2. The selection of parameters and sensor locations was the result of a compromise between cursory and excessive instrumentation. Consequently, only single-point measurements have been made of the various parameters expected to influence radon entry and indoor radon variation.

We can conceptually divide these parameters into three groups: (1) the outdoor and indoor

*Table 1. Principal Physical Characteristics of the Three Houses Selected for This Study*

PU-2

- Completely exposed to surroundings.
- Two stories with full basement (all sides communicate with ambient).
- Basement has windows which are nailed closed.
- HAC used both for heating and cooling. Combustion heating.
- Leaky return ducts in basement.
- Gravel bed under slab.

PU-21

- Fully surrounded by landscaping.
- Medium sized house: Single-story with partial basement (only 2 sides communicate with ambient).
- Basement has windows one of which is opened in summer.
- HAC used both for heating and cooling. Combustion heating.
- Leaky return ducts in basement.
- Gravel bed under slab.

PU-22

- Partially exposed to surroundings
- Large house: Three stories with partial basement (only 2 sides communicate with ambient).
- Basement without windows.
- Air-handler used only for cooling. Steam heating.
- Second and third floors cooled zonally. First floor not cooled.
- Sand bed under slab.

*Table 2. Description of Parameters Measured Continuously*

| | | |
|---|---|---|
| 1. | TB | Temperature of air in the basement. ($^{o}C$) |
| 2. | TL | Temperature of air in the living room. ($^{o}C$) |
| 3. | TA | Ambient temperature of air. ($^{o}C$) |
| 4. | W | Wind speed as measured at the weather station. (m/s) |
| 5. | TS | Temperature of soil below the slab of the house. ($^{o}C$) |
| 6. | AH | Air Handler i.e., fan to distribute hot and/or cold air. (fraction on-time) |
| 7. | DPAB | Pressure difference between ambient and basement. (Pa.) |
| 8. | DPSB | Pressure difference between subslab and basement. (Pa.) |
| 9. | DPLB | Pressure difference between living room and basement. (Pa.) |
| 10. | RNB | Radon level in the basement. (pCi/L) |
| 11. | RNL | Radon level in the living room. (pCi/L) |
| 12. | RNS | Radon level under the slab of the basement. (pCi/L) |
| 13. | RND | Radon level in subslab drain. (pCi/L) |

(Temperature differences have also been used in the study:
DTBA - temperature difference: (TB - TA)
DTLA - temperature difference: (TL - TA)
DTBS - temperature difference: (TB - TS)).

temperatures, the wind, and the air handler on-time; (2) pressure differences; (3) indoor radon levels. The first group is responsible for causing variations in the second and third groups. We did not measure direct effects related to resident behavior (opening windows, kitchen/bath exhaust ...).

The objective of the modeling has been to explain the underlying variation in indoor radon levels in terms of the variation in certain physical driving forces. To explain long-term variation, we have chosen weekly-averaged data over the entire year, since these data tend to be statistically robust. To investigate seasonal effects, like mode of house operation, we separately modeled summer, winter, and swing seasons using daily-averaged data. Finally, when more detailed diurnal variations were investigated, we chose the data in the form in which it was recorded, at half-hourly time intervals.

## WEEKLY-AVERAGED DATA OVER THE ENTIRE YEAR

A comprehensive investigation of all physically appropriate linear regression models for the important physical parameters (including indoor radon concentrations) has been described in detail by Reddy et al. (1990). We find that, for all three residences, weekly averaged run times of the air handler (i.e., AH) and basement and living area temperatures (TB, TL) are all strongly correlated with outdoor temperatures (TA), ($R^2 \approx 0.7$ - $0.9$). Pressure differences and temperature differences between basement and outdoors (DPAB and DTBA) are also strongly correlated ($R^2 > 0.9$) for all three houses. All these models were found to have physically meaningful parameters, and the $R^2$ values could not be appreciably improved after the inclusion of a few terms.

Simple models involving only indoor-outdoor temperature differences (DTBA or DTLA, both representative of the stack effect) predict weekly radon variation about as well as do models involving pressure difference variables and radon values at other house locations. Representative regression models for both basement and living-area radon concentrations and for all three houses are given in Table 3 and plotted in Figure 1 together with observed data. For PU-2, PU-21, and PU-22, the $R^2$ values were respectively about 0.35, 0.80 and 0.55. The models are most accurate for PU-21. The models for PU-22 fit best during summer when the air handler is on (the house has steam heating during winter). For PU-2, the models seem to have captured the year-long trend, though the week-to-week variations are not well predicted.

Living-area radon variation (RNL) is better explained (higher $R^2$) than that of basement radon (RNB). This is surprising, since radon generally enters the house via the basement and is then entrained upwards to the living area. The forcing functions being the same for RNB and RNL, one

*Table 3. Regression Models for Weekly Averaged Indoor Radon Concentrations. Radon concentrations are in units of pCi/L and temperature differences in °C.*

| | | $R^2$ |
|---|---|---|
| Basement radon: | | |
| PU-2: | RNB = 14.6 + 0.602 * DTBA | 0.34 |
| PU-21: | RNB = 16.3 + 10.1 * DTBA | 0.79 |
| PU-22: | RNB = 48.3 - 0.316 * DTBA - 32.4 * AH | 0.59 |
| Living area radon: | | |
| PU-2: | RNL = 9.86 + 0.292 * DTLA | 0.30 |
| PU-21: | RNL = -11.8 + 6.03 * DTLA | 0.84 |
| PU-22: | RNL = 4.69 + 0.927 * DTLA | 0.56 |

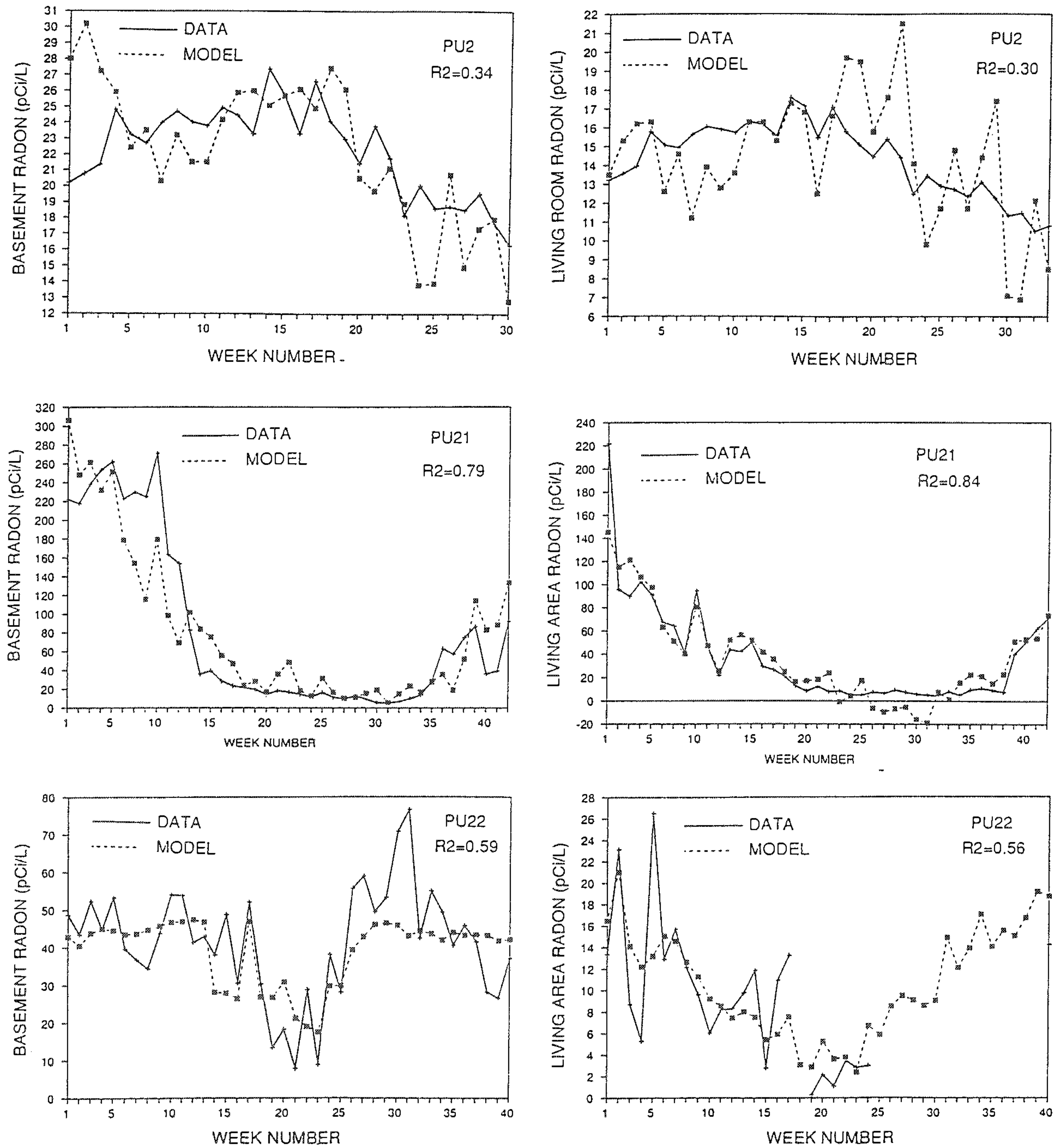


*Figure 1. Observed and Model Predicted Time Plots of Weekly Average Indoor Radon Levels. The regression models are given in Table 3.*

would have expected models to better predict RNB variations. Table 3 shows that there is much greater variation in quality of fit ($R^2$) of the regression models across houses than between the two models (for basement and living-area radon) in the same house. Apparently, whatever variability the models fail to account for is dominated by house-level factors that reduce the goodness-of-fit in basement and living-area radon models for the same house in similar ways.

Simple models involving only DTBA or DTLA (representative of the stack effect) were found to predict weekly radon variation as accurately as models involving pressure differences and radon values at other locations in the house. We had expected the latter models to be more powerful. The result may be due to the fact that our present experimental design involves only single point measurements of a particular parameter in each zone.

Our most important conclusion from the modeling of weekly-averaged radon is that the single dominating parameter which can explain radon variations over the entire year is the indoor-outdoor temperature difference (either DTBA or DTLA, which are strongly covariant). Our study highlights the fact that this natural driving force influences indoor radon levels to an extent which depends on the characteristics of the house. (For example, this temperature difference has much better explicative power for PU-21 than for PU-2.) The HAC effect is secondary, but non-negligible; because of multicollinearity between the temperature difference parameters and AH, the isolated effect of HAC is difficult to evaluate.

## DAILY-AVERAGED DATA DURING DIFFERENT SEASONS

To discuss *seasonal* variations, daily-averaged data were analyzed for two houses (PU-21 and PU-22). Since it is likely that different physical influences dominate during different operating modes of the house, and that the same physical effect may have varying degrees of influence on indoor radon levels during different times of the year, a seasonal analysis would provide insight into important aspects of indoor radon dynamics.

As illustrated for PU-21 in Figure 2, we defined seasons based on HAC operation and variation in DTLA (and TA). The five seasonal time scales identified for this study (three for PU-21, two for PU-22) are shown in Table 4. We have found that the most powerful radon regression model structures (other than those where radon itself is an exogenous variable) include lag terms for temperature differences and for air-handler on-time. We have also found that the autocorrelation coefficients for DTBA, RNB and RNL show strong correlation (coefficients greater than 0.8), while the partial autocorrelations for lags greater than one day are not statistically significant at the 95% level. These results are discussed more fully by Reddy et al. (1990).

The $R^2$ values for the most powerful linear regression models for indoor radon concentrations are also given in Table 4 for each of the five seasonal periods. We note that all but two of the $R^2$ values are between 0.5 - 0.9. Figure 3 compares the model predictions to the daily averaged measured indoor radon data for PU-21 summer. The corresponding linear regression models are also given in Table 4.

The models for indoor radon levels are physically consistent over seasons and across houses. Models involving temperature difference variables explain indoor radon variation as well as, if not better than, models involving pressure difference variables. Such a conclusion was also reached when weekly-averaged data were analyzed in the first part of this study.

## HALF-HOURLY DATA

Regression modeling of radon data at half-hourly time scales may reveal the significance of momentary effects of certain parameters (effects that are not important for daily or weekly averaged data). We have indeed found situations where the presence of recurrent short-term physical effects is particularly strongly represented in the data. We present results, discussed more fully by Hull (1990), for the basement and subslab (in-the-drain) radon levels in PU-22. These exhibit strong diurnal patterns that seem to be linked to changes in temperature and pressure.

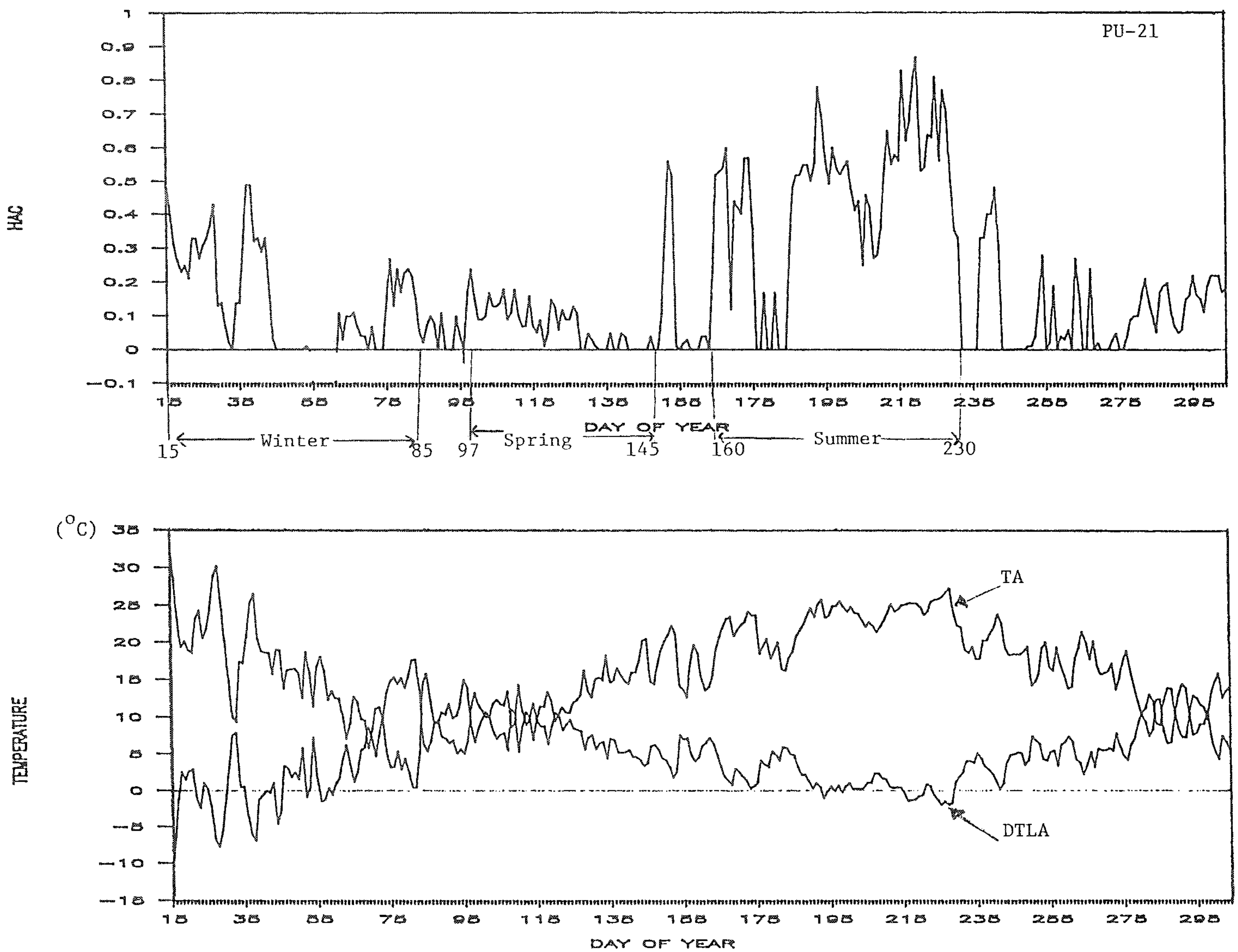


*Figure 2. Time Plots of Daily Averaged HAC On-Time and Temperature for PU-21. The three seasonal periods chosen for analysis are also s*

*Table 4. Various Seasonal Periods Chosen to Analyze Daily Average Data. The $R^2$ values of the best linear regression models for indoor radon concentrations are also shown.*

| House | Season | Julian Days (1988) | No. of data points | Remarks | $R^2$ RNB | $R^2$ RNL |
|---|---|---|---|---|---|---|
| PU-21 | Winter | 15-85 | 64-70 | TS missing | 0.46 | 0.68 |
| | Spring | 97-145 | 49 | Low HAC use | 0.92 | 0.79 |
| | Summer* | 160-230 | 71 | Large HAC use | 0.64 | 0.50 |
| PU-22 | Summer | 166-230 | 65 | Large HAC use | 0.59 | 0.61 |
| | Fall | 280-343 | 64 | No HAC use, RNL missing | 0.31 | - |

*Data from this period are plotted in Figure 3. The best linear regression models identified are:

$$RNB = 10.0 - 1.26 * DTLA + 1.03 * [DTLA]_{1\text{-}day} + 1.29 * DTBA + 2.09 * [DTBS]_{1\text{-}day}$$

$$RNL = 3.84 + 0.614 * [DTLA]_{1\text{-}day} + 4.49 * AH$$

The subscript following the bracket represents the number of days of lag. Radon concentrations are in units of pCi/L and temperature differences in $^{o}C$.

The data were divided into nine periods (5 in summer and 4 in fall) that range from 7 to 11 days in length (Table 5). The period length for modeling is a compromise between using short periods which produce better fits and long periods which provide a much more comprehensive model.

The radon levels in the basement vary from 20 to 150 pCi/L, while those in the drain range between 1000 and 15000 pCi/L.[1] The radon data that were studied have two distinct patterns: summer with the drains open, and fall with the drains blocked. Quick scans of the data revealed a strong diurnal pattern. During the summer (not shown), the basement and drain radon levels are highly correlated, peaking in the middle of the night and bottoming out during the heat of the day. The fall patterns (see Figure 4) show a similar diurnal cycle, but the drain radon now peaks during the hottest part of the day, 12 hours out of phase with the basement radon.

The best model structures for drain radon have been found to involve two temperature differences, (TA-TS) and (TA-TB), both using present and lagged terms. For basement radon, models involving RND and DPBA have been found to be most explicative during summer periods, while those involving (TA-TB) (or DPBA) only are adequate during fall periods (probably became the drain system was closed). The model $R^2$ values for both RND and RNB are given in Table 5; they are seen to vary little from period to period, explaining between 63 and 86 percent of the variation.

The most powerful models for RND and RNB are difficult to interpret since they contain several lagged parameters. The significant times series parameters also vary widely from period to period. In order to simplify the models, another series of regressions was performed with each parameter

[1] *The extraordinary high levels in the drain led us to test the extent to which the drain provides the primary means of radon entry into the basement. On Julian day 211, the drainage system was blocked. This significantly reduced the radon in the basement for about 10 days, but subsequently, the radon concentration climbed back to its original level. This experiment reinforced the hypothesis that blocking the path of least resistance does not eliminate the radon problem but only causes the radon to find a different path of flow.*

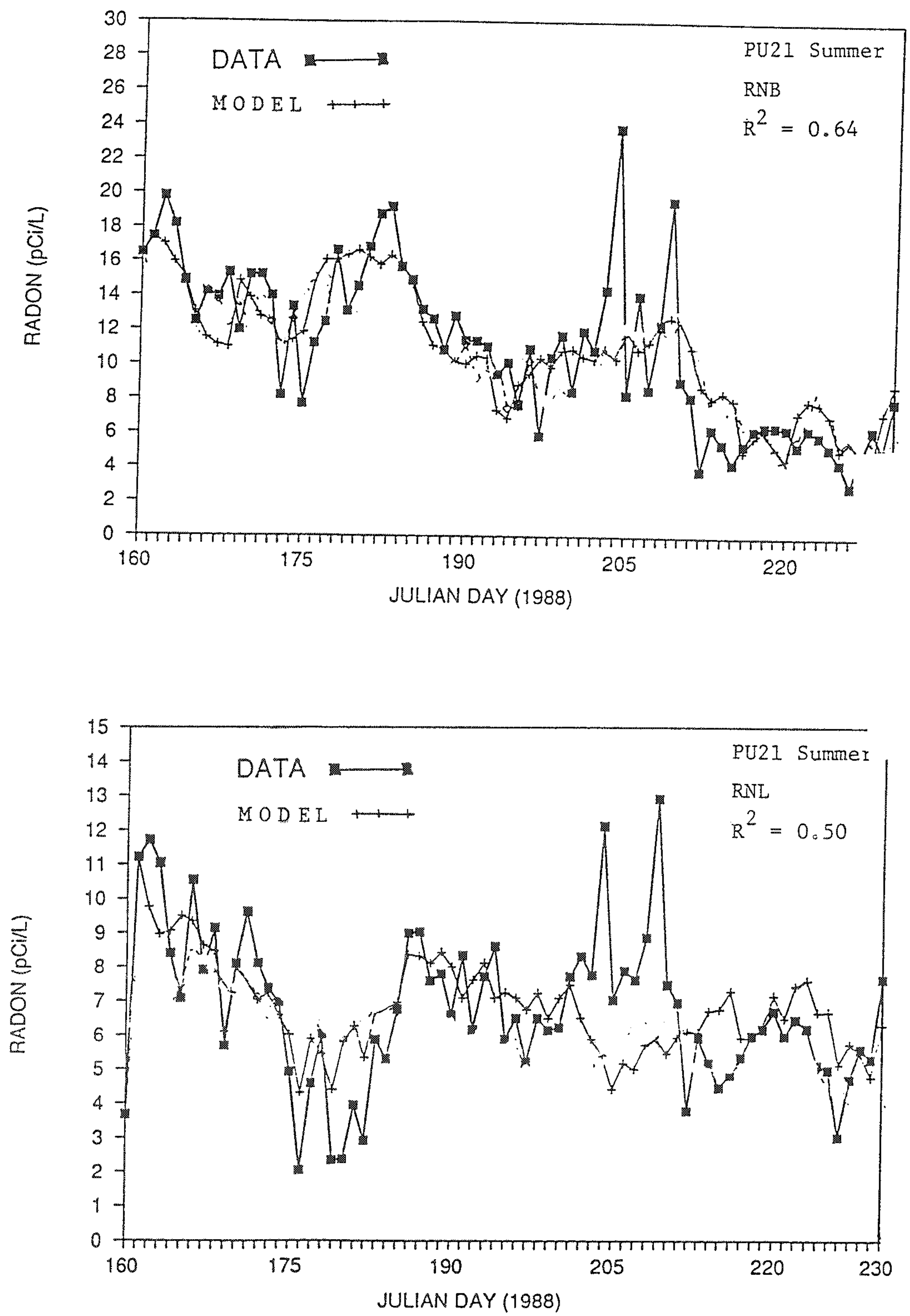


*Figure 3. Observed and Model Predicted Time Plots of Daily Average Indoor Radon Levels for PU-21 Summer. Regression models are given in Table 4.*

*Table 5. Data Periods Chosen to Analyze Half-Hourly Data of PU-22. The $R^2$ values of the best linear regression models for indoor radon concentrations are also shown.*

| Period | Julian Days (1988) | Number of days | $R^2$ RND | $R^2$ RNB |
|---|---|---|---|---|
| Summer (drains open): | | | | |
| 1 | 148-154 | 7 | 0.80 | 0.86 |
| 2 | 165-174 | 10 | 0.83 | 0.80 |
| 3 | 175-184 | 10 | - | 0.67 |
| 4 | 185-194 | 10 | 0.76 | 0.84 |
| 5 | 195-203 | 9 | 0.74 | 0.81 |
| Fall (drains blocked): | | | | |
| 6 | 233-242 | 10 | - | 0.78 |
| 7* | 243-252 | 10 | 0.72 | 0.63 |
| 8 | 253-262 | 10 | 0.63 | 0.75 |
| 9 | 263-273 | 11 | 0.76 | 0.82 |

*Data from this period are plotted in Fig. 4. The best simplified linear regression models are:

$$RND = 5820 + 2450\ [TA\text{-}TS]^{+}_{2hr} - 485\ [TS\text{-}TA]^{+}_{2hr} - 4940\ [TA\text{-}TB]^{+}_{2hr}$$

$$RNB = 15.7 + 6.2\ [TB\text{-}TA]^{+}_{1.5hr}$$

The subscript following the bracket represents the number of hours of lag. The superscript + indicates that negative values of the parameter are set to zero. Radon concentrations are in units of pCi/L, and temperature differences in $^{o}C$.

restricted to a single lag. These simplified models sacrifice about 5 to 10 percentage points in terms of $R^2$ values, but they are easier to interpret. How well these regression model structures explain the large diurnal fluctuations in RND and RNB during fall period 7 can be gauged from Figure 4, which reveals that the simplified models (given in Table 5) are generally very good and show no consistent bias. Figure 4 and the simplified model structures suggest a relatively simple system of air dynamics, where the drain works as a thermally induced pump, pushing radon into the basement during one phase of a diurnal cycle and removing radon during the other phase. As the temperature differences between the soil, the basement, and the outdoors change sign from summer to fall, an entirely new pattern of drain radon and basement flow emerges which

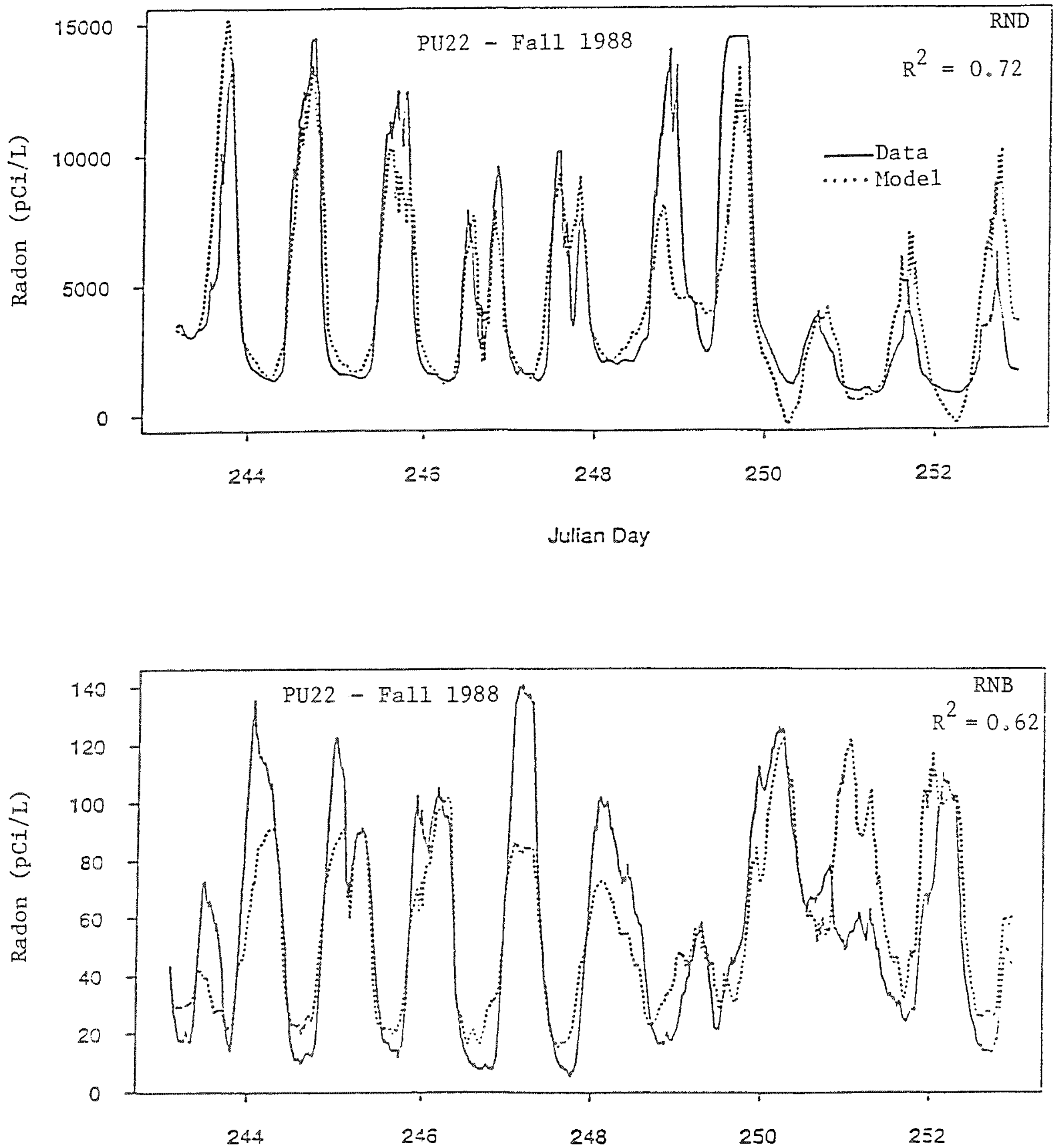


*Figure 4. Observed and Model Predicted Time Plots of Half-Hourly Drain and Basement Radon Levels for PU-22. The regression models are given in Table 5.*

nevertheless has been shown to be consistent with our simplified physical analogue of a pump system.

## CONCLUSIONS

This paper has presented regression models for indoor radon levels in three residences at three different time scales: weekly-averaged data spanning an entire year, daily-averaged data over seasonal periods, and half-hourly data over two weeks. The stack effect (parameterized by either DTBA and DTLA - which are strongly collinear) has been found to be the single most dominant driving force controlling indoor radon levels at all three time scales. Simple physical models identified are generally satisfactory, explaining 50-80% of the variation in the indoor radon levels at all three time scales.

## ACKNOWLEDGMENTS

Although the research described in this article has been funded wholly, or in part, by the United States Environmental Protection Agency through Cooperative Agreement No. CR-814673, it has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

## REFERENCES

Dudney, C. S., L. M. Hubbard, T. G. Matthews, R. H. Socolow, A. R. Hawthorne, K. J. Gadsby, D. T. Harrje, D. L. Bohac, and D. L. Wilson. 1988. *Investigation of Radon Entry Effectiveness of Mitigation Measures in Seven Houses in New Jersey*, Oak Ridge National Laboratory report ORNL-6487.

Hull, D. A. Time Series Linear Regression of Half-Hourly Radon Levels in A Residence, paper presented at the 1990 International Symposium on Radon and Radon reduction Technology, Feb. 19-23, Atlanta, Georgia, 1990.

Reddy, T. A., F. B. Molineaux, K. J. Gadsby, and R. H. Socolow, Statistical Analysis of Radon Levels in Residences using Weekly and Daily Averaged Data, PU/CEES Report No. 249, Princeton University, April 1990.