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RADON DYNAMICS IN SWEDISH DWELLINGS: A STATUS REPORT

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ABSTRACT

A status report of a long term study on radon entry into Swedish dwellings is given. Both physical modelling and continuous measurements of radon and other relevant parameters in real home environments are being used in the investigation. Building characteristics typical of Swedish dwellings and geological factors typical of Swedish ground are discussed with regard to their relevance to radon entry. The research homes used in this study are described and factors affecting radon entry are compared to similar factors in the New Jersey Piedmont research houses. Current results of the measurements in the research homes are presented and the dynamic modelling being developed to study the temporal behavior of radon indoors is introduced.

INTRODUCTION

Several researchers in recent years have begun to focus on understanding the various mechanisms driving radon entry into dwellings, and to what extent these mechanisms cause indoor radon concentrations to vary with time. Driving forces such as temperature differences between the indoors and outdoors, the wind, and the effects of indoor ventilation systems have been observed in relationship to temporal variations in indoor radon concentrations (1). Understanding these mechanisms driving radon entry will ultimately be useful in designing more effective ways to mitigate homes with high indoor radon concenrations, and in constructing better protocols for measuring radon indoors.

Our own research focuses on understanding the behavior of some basic parameters associated with radon entry and movement indoors. The quantity of main interest is the amount of air infiltrating a dwelling from the radon-containing soil gas versus the relatively radon-free outdoor air. We hope to understand how the amount of air infiltrating a dwelling from these two different sources changes with relation to each other, with time, and with environmental driving forces such as temperatures inside and outside the dwelling and the wind. We are using both theoretical modelling and measurements in real houses to obtain a better understanding of these processes.

This report is organized as follows. We begin with a brief description of building characteristics which are typical in Sweden, which is intended to provide a background for understanding the types of radon problems which exist in Sweden. This discussion is followed by a description of our current data collection procedures in two research houses, and the houses are described and compared to the houses in the Piedmont Project (1). We conclude with a report on our ongoing efforts at modelling indoor radon concentrations.

BUILDING CHARACTERISTICS OF SWEDISH HOUSES

THE SOIL

The radon concentration in the soil gas in Swedish soil has always been found to be at least 5000 Bq/m^3 at a depth of 1 meter. It is usually between 20,000-40,000 Bq/m^3 in moraine and 30,000 - 150,000 Bq/m^3 in gravel. When the soil contains some alum-shale the radon concentration can be as high as $1\text{-}2\times10^6$ Bq/m^3. Moraine is very common in Sweden and other glaciated terrains such as in Canada and the northern United States. In addition, eskers are very common in Sweden, which are long ridges or mounds of sand, gravel, and boulders deposited from flows under or around stagnated glaciers from the last ice age, and the soil is very permeable. The combination of the rather high radon concentration in the soil air and the permeability of the soil give most of Sweden a rather high potential for radon ingress into houses.

BUILDING MATERIALS AND BUILDING FOUNDATION

Most Swedish one-family houses are built of wood, with the exception of the Skåne landscape in the south of Sweden, where most houses are built of stone materials. During the last decade brick and concrete have been more common in the whole country. In about 10% of the 1976 building stock, (which includes both one-family houses and apartments in multi-family houses), alum-shale based concrete had been used. Alum-shale based concrete contains enhanced levels of ^{226}Ra of between 600 - 4300 Bq/kg, and was produced between 1929 and 1974. The alum-shale materials give radon levels in many houses in the range of 400-800 Bq/m^3. Most multi-family houses are built of concrete or brick.

Houses built with basements (or cellers) are the most common in Sweden. Before 1940, houses built with crawlspaces were about equally common as those built with basements. During the 1970s, houses built with a slab-on-grade became increasingly more popular. The proportion of the housing stock, as a function of year when built, with either slab-on-grade, crawlspace, or basement (celler) can be seen in figure 1.

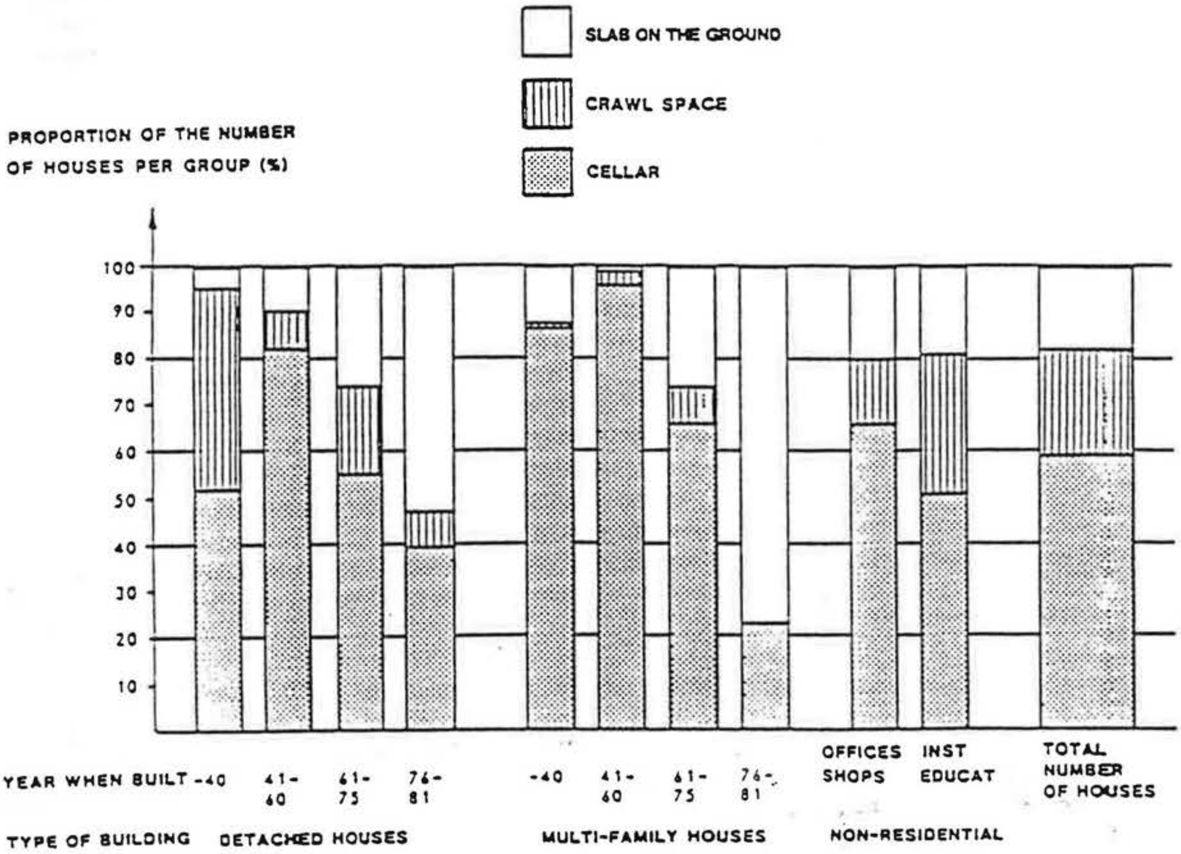


Figure 1. Type of building foundation in Swedish buildings.

VENTILATION

The most common ventilation system in Swedish detached houses is natural draught ventilation combined with a kitchen fan. An increasing number of houses built during the 1970's used mechanical exhaust ventilation, which began to be changed to mechanical inlet and outlet ventilation with some kind of heat recovery during the 1980's.

The older multi-family houses have natural draught ventilation and an increasing ratio of those built since 1945 have mechanical exhaust ventilation. Since 1980 mechanical ventilation has been required in multi-family houses.

Our current research program on radon dynamics in Swedish homes concentrates on understanding radon entry in two houses which are somewhat typical in design. We describe them next, and discuss how they differ from houses one of us has studied in a previous research project called the Piedmont Project, which was funded by the USEPA (1).

MEASUREMENTS IN RESEARCH HOUSES

We currently have two houses for study which are of somewhat typical Swedish design. During the past year we have instrumented the two houses for collecting continuous data, which includes environmental temperatures in a variety of locations indoors and outdoors, pressure differences across the building shell in a variety of locations, and radon gas concentrations in differenct indoor or subfloor zones. The data are recorded electronically and hourly averaged data are stored in a computer located at the house. The two houses both have indoor radon concentrations which average between 100-200 Bq/m3 in the living level and the source of the radon is the soil gas.

The first house, (labeled 901), was instrumented in March, 1990, and data collection began at that time. This house was built in 1960, and the substructure consists of a basement with two attached crawlspaces, and a single living level floor above the substructure. The basement is a finished working space with a poured concrete slab. Both crawlspaces, which can be accessed from the basement through small doors with vents, have dirt floors. The house is of wood construction with a concrete block substructure. It is heated by hot water radiators with the water heated by an oil burner located in an attached room adjacent to the house. The house contains a natural draught ventilation system. This house will be the more difficult to model of the two research homes, because of its more complicated substructure.

The second house, (labeled 902), was instrumented in October, 1990, and data collection began Nov. 1. This house was built in 1907, and is entirely of wood construction. It is located on an esker and thus the soil is rather sandy and permeable. The structure of 902 is simple, consisting of a rectangular two-storied house on top of a small crawlspace on top of the ground. The house is heated with electrical radiators and contains a natural draught ventilation system. We hope the simplicity of the structure, shown in figure 2, will be useful in our modelling efforts.

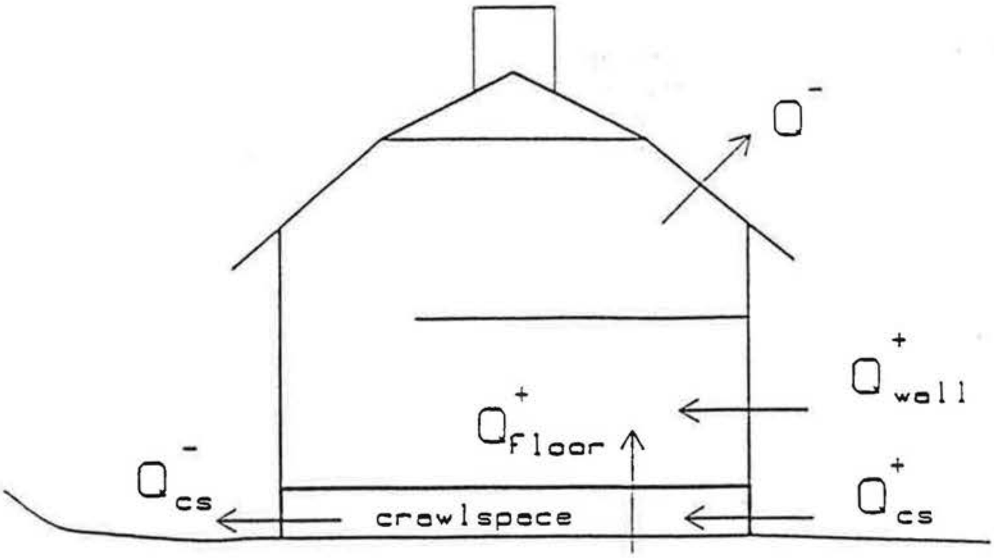


Figure 2. Research house 902, which is located on an esker. The Q's label air inflows and outflows needed for modelling.

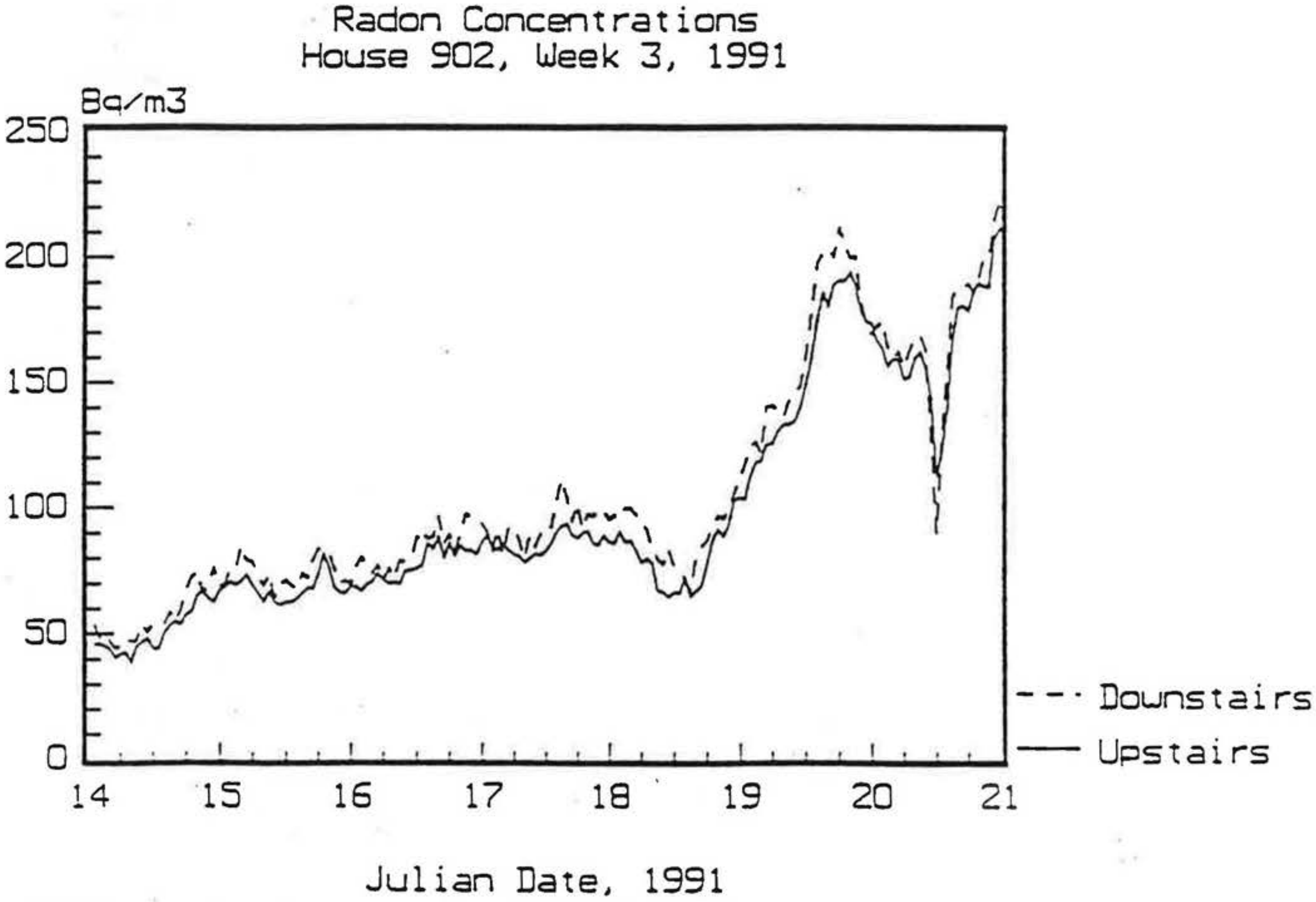


Figure 3. Hourly averaged radon concentrations.

Despite the fact that House 902 is a two-story house, the two levels are connected by considerable open space, and it acts very much like a single indoor zone. Figure 3 shows the radon concentrations upstairs and downstairs during one week in January, 1991, and the close agreement between the two indicates good mixing of the indoor air. The pressure difference between the downstairs and upstairs has also been continuously measured and is never larger than a few tenths of a Pascal. We thus treat House 902 as a single indoor zone in our radon flow model.

Both homes have natural draught ventilation, which is the most common type of ventilation system in Swedish detached houses. Natural draught ventilation does not work very well in the summer season when the outdoor temperature is about the same as the indoor temperature and the house has a low air exchange rate, as do most houses in Sweden. However, in the fall, winter, and spring natural draught is a rather efficient means of ventilating. Also, natural draught ventilation does not add any perturbing pressure differences across the building shell, as have been observed before in the New Jersey Piedmont homes due to unbalanced air handlers, which greatly complicates the modelling of the airflows and infiltration. Figure 4 shows the daily radon concentration varying nicely with the outdoor-indoor pressure difference and temperature difference in research house 901, showing that during non-windy days infiltration should be well described in a model using stack pressures alone.

The most significant factor affecting the daily dynamics of radon entry which differs in the current research from the Piedmont Project is the type of ventilation in the homes. All seven of the Princeton/ORNL research homes had forced air ventilation. The difference between the daily variations in the radon concentrations when the forced air ventilation system was in use versus when electric heaters were brought in to heat the home was quite large in the one home where this experiment was performed (2). In most cases the pressure differences across the building shell created by the air handler use were dominant over the effect of the indoor-outdoor temperature differences in their effect on the hourly variations of the radon.

Other differences between these research houses and the Piedmont research houses are the following. The Piedmont homes generally had unfinished basements with hollow block walls, a poured concrete slab with either a perimeter drain or a perimeter crack, and a sump. The hollow block walls played a role in radon entry because of their extremely porous nature, as did the perimeter drains and sumps with their direct connection to soil gas. These obvious entry routes usually make mitigation straightforward, by enough sealing of the entry routes to make depressurizing the area beyond the barrier created by the slab and walls possible. As is generally known now, this can usually be accomplished by sealing of perimeter drains and sumps and applying suction with a fan to the subslab. These methods are not suitable in the current Swedish research homes because of the exposed dirt floors in the crawlspaces. Either basement or crawlspace ventilation or soil ventilation using a radon well, especially in house 902 which has such permeable soil, will be applied here, if mitigation is desired by the homeowners.

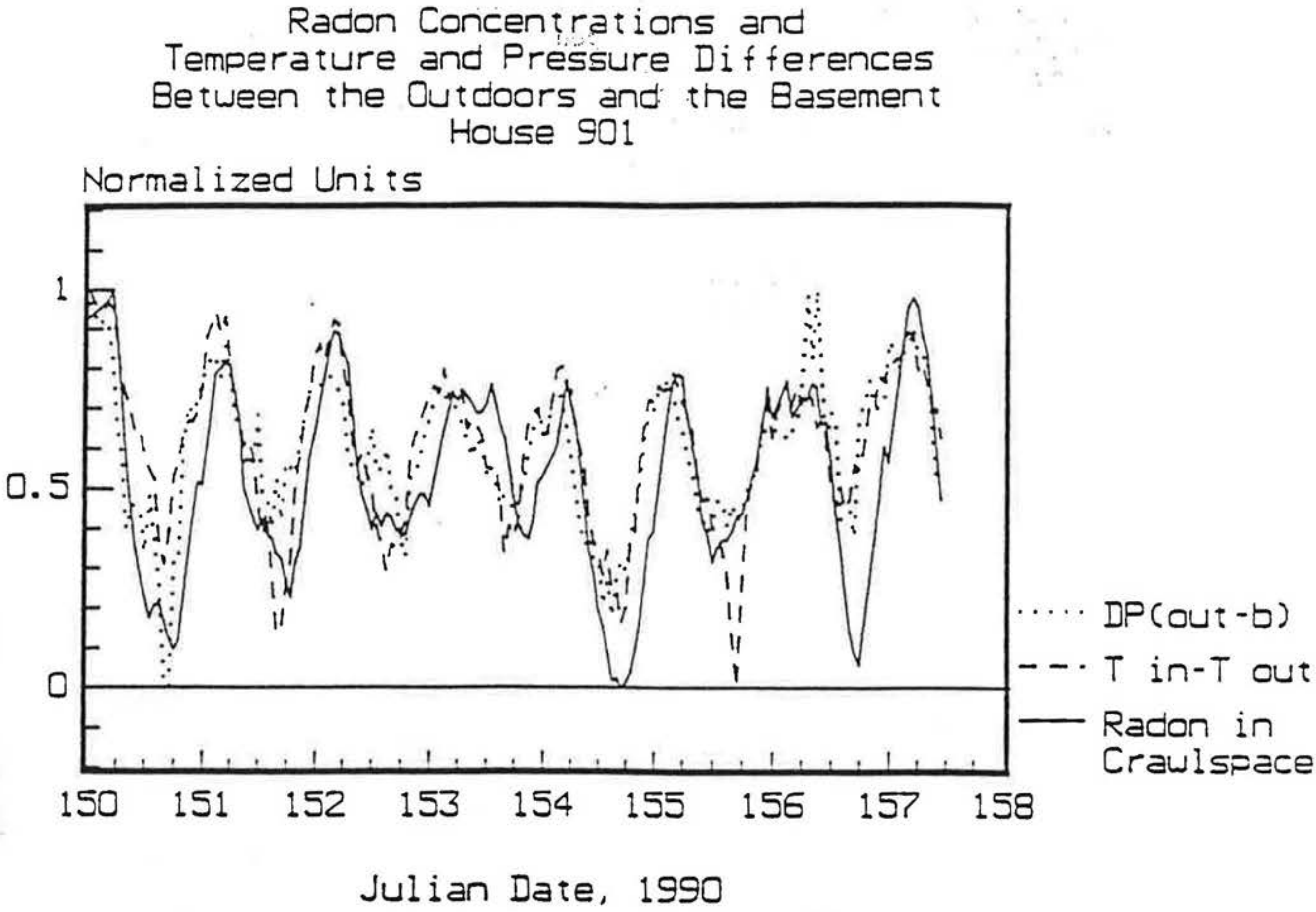


Figure 4. The curves were normalized to facilitate comparison. Maximum and minimum values for each curve are: 1) radon concentrations, 670 and 326 Bq/m^3, 2) temperature differences, 16 and -12 °C, and 3) pressure differences, 1.7 and -1.1 Pa.

MODELLING RADON ENTRY

We have previously described a model for calculating the time dependent radon concentration in different indoor zones, called the radon flow model (1). It takes as its input the airflows between indoor zones and between the indoors and the outdoors, at each time period Δt, and the initial radon concentration in each zone. It gives as its output the modelled (or predicted) radon concentration in each zone as a function of time. The equations for predicted radon in zone i, neglecting the radon decay term because for our research houses it is insignificant compared to the flow terms, are the following.

$$[Rn(t)]_i(\text{predicted})=[Rn(t-1)]_i+[Rn(t)]_i(\text{inflow})-[Rn(t)]_i(\text{outflow}) \qquad (1)$$

where

$$[Rn(t)]_i(\text{inflow}) = \frac{\Delta t}{\text{vol}_i} \times [\Sigma_j Q(t-1)_{j \to i} \times [Rn(t-1)]_j + Rn'_i] \tag{2}$$

$$[Rn(t)]_i(\text{outflow}) = [Rn(t-1)]_i \times \frac{\Delta t}{\text{vol}_i} \; \Sigma_j Q(t-1)_{i \to j} \tag{3}$$

and where

i,j	index the different indoor zones and the outdoors;
$Q(t)_{i \to j}$	is the flow from zone i to zone j during the time period from t-1 to t;
$[Rn(t-1)]_i$	is the predicted radon concentration in zone i at t-1;
vol_i	is the volume of zone i;
Δt	is the short time period during which radon concentrations in each zone are held constant; and
Rn'_i	is a radon entry rate from outdoors, which is 0 except in the zone or zones which have flow directly from the soil gas.

The tricky part in implementing this model is obtaining the airflows between indoor zones and between indoor zones and the outside. In our previous application of this model we used as input airflows in a research home which were measured using a multi-tracer gas system. That system measured time-varying airflows at the same time we were measuring time varying radon concentrations, which gave us the ability to check the modeled radon concentrations. The agreement between the modelled and the measured radon in the two indoor zones was quite good, indicating how well the measured airflows represented the true situation (1). It is not always possible to have a multi-tracer gas system available in research houses, however. In fact only a few such systems exist in the world.

The next best alternative to measuring the airflows is to model them. In fact, modelled airflows are more desirable than measured ones from a pedagogical viewpoint because, once the airflows are properly modelled, we can use the model to learn more about radon entry by altering the input parameters.

Our current modelling efforts have been concentrated on developing a simple formulism for modelling the airflows, treating the air infiltrating from the soil gas separately from the air infiltrating from the outdoor air. There exists several indoor airflow and infilration models which could be adapted for use in indoor pollution transport models, such as the radon flow model. However, they require detailed house specific knowledge on leakage characteristics, such as the location and type of flow paths beween zones and around the building shell, and they are often cumbersome and difficult to use.

Our initial goal is to see how simple we can make an infiltration model and retain enough of the physics to learn something from the model. Consider the simplest case for modelling and for predicting the airflows and the radon concentration. That would consist of simply one indoor zone connected to both the outdoors and to a source of radon in the soil gas. We have been fortunate enough to obtain just this type of house for one of our research homes; as mentioned earlier in connection with figure 3, House 902 can be treated as a single indoor zone. This has made it rather easy to begin our effort at modelling airflows and predicting radon and check the predictions on a simple, but real, home environment. The flows labeled in figure 2 are the relevent airflows to model for a single indoor zone. Q^{+}_{floor} is the airflow which will carry the radon into the house from the crawlspace. For modelling radon entry during the winter months we assume the flow from the indoors to the crawlspace is negligible.

We have begun by considering only the temperature difference between the indoors and the outdoors as the driving force for air infiltration. Because of the large number of days in Sweden during the fall, winter, and spring months which have significant temperature differences between the indoors and the outdoors, stack effect pressure differences caused by differences in the indoor and outdoor temperatures are an important driving force for air infiltration in Swedish houses.

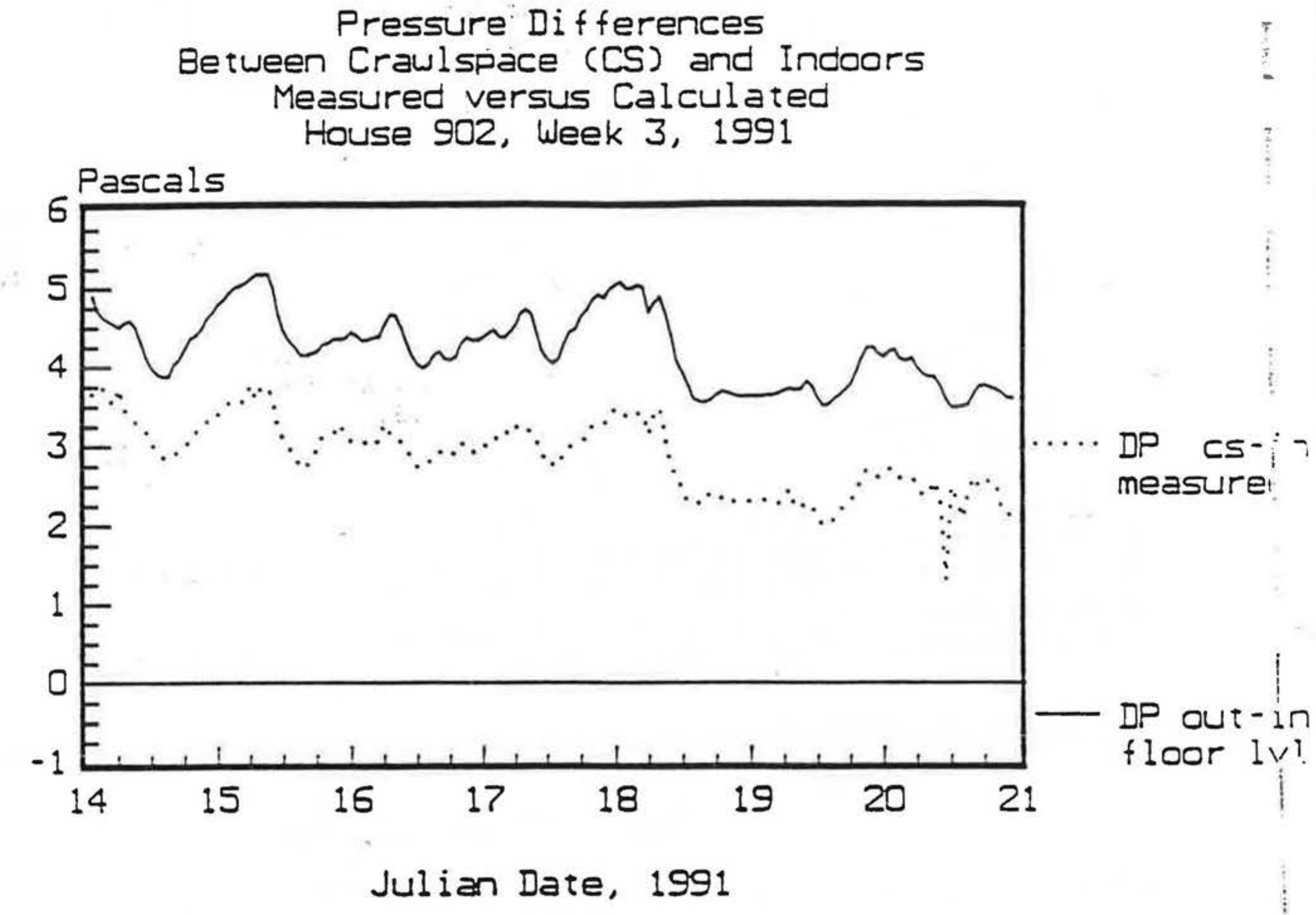
The stack pressure is the difference in pressure difference between the indoors and the outdoors at one level, or height, on the building versus another level on the building. But the pressure difference must be known at one of the heights to know it at any other, which is why the stack pressure is often referenced to a neutral pressure plane, labeled β_o, where the pressure difference is zero. We also use the neutral pressure plane as a point of reference, and find that often one can solve the continuity equations exactly for β_o.

The stack pressure difference between the outdoors and a single indoor zone is given (in Pascals) by:

$$\Delta P_s(\beta) = -\rho_{out} g H_s (\beta - \beta_o)\left(\frac{T_{in} - T_{out}}{T_{in}} \right) \qquad (4)$$

where ρ_{out} is the density of the outdoor air, g is the acceleration due to gravity, (m/sec^2), T_{in} and T_{out} are indoor and outdoor temperatures, (K), β is a dimensionless height, $z = H_s \beta$, (and β_o refers to the height z_o where the indoor pressure equals the outdoor pressure), and H_s is the height dimension of the building over which the stack pressure is being calculated, (m). The sign convention for equation (4) and all pressure differences reported in this paper is the pressure outdoors minus (-) the pressure indoors.

We have chosen a week in January, 1991, during which there was little wind, to compare the measured pressure difference between the indoors and the crawlspace, recorded hourly from a transducer measuring in the center of the floor area, with the calculated stack pressure difference at the floor level, (β=0), using equation (4). The hourly measured indoor and outdoor temperatures and the stack height of house 902 are the input to equation (4). This comparison is shown in figure 5, and it is encouraging how well the stack pressure reproduces the measured pressure difference during this non-windy week. The bimp on day 20 in the measured pressure difference and also in the radon concentrations shown if figure 3 correspond to a time when the homeowner aired the house.



CONCLUSION

We are currently modelling airflows using the stack pressures alone to determine infiltration. The stack pressures are modelled using temperatures measured at the research house. We will check the modelled radon concentrations using data measured at the research house during non-windy days or weeks. Pressure differences modelled from the effect of wind are intended to be added separately to the model. Our ultimate goal is to determine to what approximation we can model indoor radon concentrations using a simple formalism based on temperature differences and the wind. Once we have determined that, we can use the model to learn more about the radon dynamics as a function of parameters, such as the leakiness to the soil gas versus the leakiness to the outdoor air. A future report will present details of the model formalism and results.

Acknowledgments. The authors thank Leif Nyblom and Hans Möre for crucial help with the instrumentation and data loggers.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred. The work described in this paper was, however, partially funded by the the CEC/NRPB Association Agreement contract No. B.16.347 UK (H), which we gratefully acknowledge.

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