Temperatures and Relative Humidities in Heated and Ventilated Crawl Spaces

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ABSTRACT

Temperature and relative humidity in a crawl space beneath a well-insulated house, ventilated by the outdoor air, vary with the season. During the summer, warm, moist outdoor air enters the relatively cool crawl space with the result that the relative humidity becomes so high that mildew can become established. This sometimes gives rise to an unpleasant smell in the crawl space, and the smell can find its way into the house. Although this is a recognized problem in Sweden, many houses are still built with this type of foundation structure.

It is preferable to avoid the use of outdoor-air-ventilated crawl spaces in their entirety and to raise the temperature of the ground beneath the building, either by means of the heat in the house's ventilation exhaust air or by a floor heating system. If so, the foundations must be designed to suit the system to be used.

This paper describes a number of designs that are theoretically suitable and for which calculations have been made and presents measured results from houses built on a number of different types of foundations. The results from the calculations and the actual measurements both indicate that heated foundations are also dry foundations. Even if moisture is trapped in the structure as a result of rain during the construction period, it need not result in damage; the heated foundation system accelerates drying out.

INTRODUCTION

Until the 1950s, the most common type of foundation used in houses not having basements or cellars was the traditional raised cottage foundation. The principle of this was that the ground floor of the house was supported on low walls that were themselves carried on "conventional" foundations: the supporting walls enclosed the space beneath the ground floor, which was high enough to allow access by crawling. A feature of this was relatively poor thermal insulation of the structure of the joists and floor above the crawl space. The floor was also seldom airtight and therefore permitted the exchange of air between the interior of the house and the crawl space. In addition, the footing of the central chimney and fireplace structure was often founded on the ground in the crawl space, thus providing a certain amount of heat input to the crawl space during the heating season. At this time, too, the ventilation openings, or airbricks, in the perimeter walls were blocked, with snow shoveled up against the walls and reducing the outward heat loss. During the summer, the openings were unobstructed, allowing outdoor air to flow into a relatively warm space, about 15°C.

Houses were often sited on high ground in order to avoid damp and mildew damage. At potential weak spots at the junction between the building and the foundation walls, the design was such that parts that were considered to be at risk from mildew or rot could easily be replaced.

At the end of the 1950s and beginning of the 1960s, a new foundation design was introduced from the USA in the form of a cast concrete slab on the ground, with thermal insulation above it. Dimensions and design details were based on the risk of condensation and rot. Investigations performed at the beginning of the 1960s (Ericsson 1960) showed that the risk of condensation was relatively slight, but that pressure-impregnated sill plates or blocks should be used as a safety precaution. This type of foundation was predominant during the 1970s, and a very large number of houses were built using it.

Toward the end of the 1970s, complaints of an unpleasant smell in these houses became increasingly common. The reason for this was to be found in the growth of mildew in the structure, with one of the areas at risk being that of floors supported on joists resting on the foundation slab. It was realized that, when designing for a low moisture content in the structure in order to prevent mildew, performance requirements were considerably more demanding than those of the earlier criteria, which were based on the risk of rot in wooden elements. This was one of the reasons why the 1980s saw an increasing return to the use of outdoor-air-ventilated crawl spaces; an improved method of foundation was required, and history had shown that the traditional raised cottage foundation was resistant to moisture.

However, the (re)introduction of the outdoor-air-ventilated crawl space did not cure the problem of odor indoors. Mildew still managed to establish itself—with resulting odor problems—in many outdoor-air-ventilated crawl spaces, with the result that the smell found its way into the interior of the house, as the floor structures were not airtight. Simplifying, there can be said to have been two reasons for the occurrence of problems: the fact that the criteria for a moisture-resistant building structure have changed with time and that insufficient attention was given in the design to the ability to withstand moisture.

We are now looking for new foundation methods that can eliminate the risks of moisture and mildew that could cause poor indoor air quality, which is the main problem

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with crawl spaces in Sweden. One such design is provided by the heated crawl space, ventilated by indoor air. The objective of this project has been to provide theoretical and practical evaluation of the performance of this type of foundation design.

OPERATATING PRINCIPLE OF HEATED FOUNDATIONS

In this paper, the term *heated foundations* refers to foundations in which a space or material is actively heated in order to ensure a dry structure. Heating may be effected either by ventilation, using warm indoor air, or by supplying heat from a heat source. The principle of an indoor-air-ventilated heated foundation is shown in Figure 1.

This project has concentrated particularly on foundation designs in which a heated, ventilated air space has been created beneath the lowermost joist structure, with this air space also being used for heating the building.

The principle of a heated foundation is that it must be

- insulated from the ground and around the perimeter walls, preferably on the outside of the perimeter walls;
- airtight, in order to avoid uncontrolled ventilation;
- at negative pressure with respect to the interior of the building, in order to prevent the ingress of radon to the building;
- designed to minimize thermal bridges in the structure.

THEORETICAL CALCULATIONS OF EXPECTED MOISTURE CONDITIONS IN CRAWL SPACES

It is relatively easy to provide a qualitative explanation of why the relative humidity in a conventional outdoor-air-ventilated crawl space will be high during the summer, solely as a result of the external air humidity. In an outdoor-air-ventilated crawl space that is continuously ventilated, the temperature only varies slightly from an average annual temperature. The temperature in the crawl space is, therefore, also relatively low, about 10°C (50°F) during the summer. Raising the temperature in the crawl space provides a simple means of dealing with the problem of high relative humidities.

Hagentoft (1992) has calculated the temperature and relative humidity in an outdoor-air-ventilated crawl space and in a warm-air-ventilated crawl space (see Figure 2). The crawl spaces are situated in the middle of Sweden. Outdoor temperature and relative humidity are shown in Figure 3. For the outdoor-air-ventilated crawl space, the design parameters have been a modest increase in the absolute humidity of $1 \cdot 10$ kg/m^3 (mass of water/unit volume of air, or $\approx$ 0.83 g/kg mass of water/mass of dry air) in the air in the crawl space compared to the outdoor air. This "moisture input" varies with the air change rate in the crawl space and with how well the moisture insulation on the ground and around the perimeter walls is made. A moisture input of $1 \cdot 10$ kg/m^3 (0.83 g/kg) should be reasonable in a well-designed crawl space. Thermal insulation is placed on the ground to reduce the effects of heat exchange. The air change rate in the crawl space has been 1.4 ach.

The warm-air-ventilated crawl space is relatively modestly insulated against the ground and around the perimeter wall, with the perimeter wall being both internally and externally insulated. The air change rate has been set at 0.4 ach, using indoor air. The moisture input to the crawl space, or rightly to the indoor air, is $3 \cdot 10$ kg/m^3 (2.49 g/kg). Studies made by Harderup (1983) show that the moisture input to the indoor air varies between $2\text{-}4 \cdot 10^{-3}$ kg/m^3 (1.66-3.32 g/kg) in an ordinary dwelling.

The calculated results (see Figure 4) are expressed as mean weekly values. For the outdoor-air-ventilated crawl

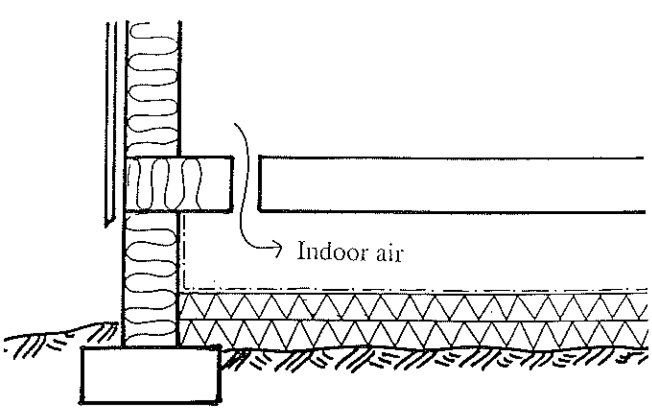

Figure 1 *The principle of an indoor-air-ventilated heated foundation.*

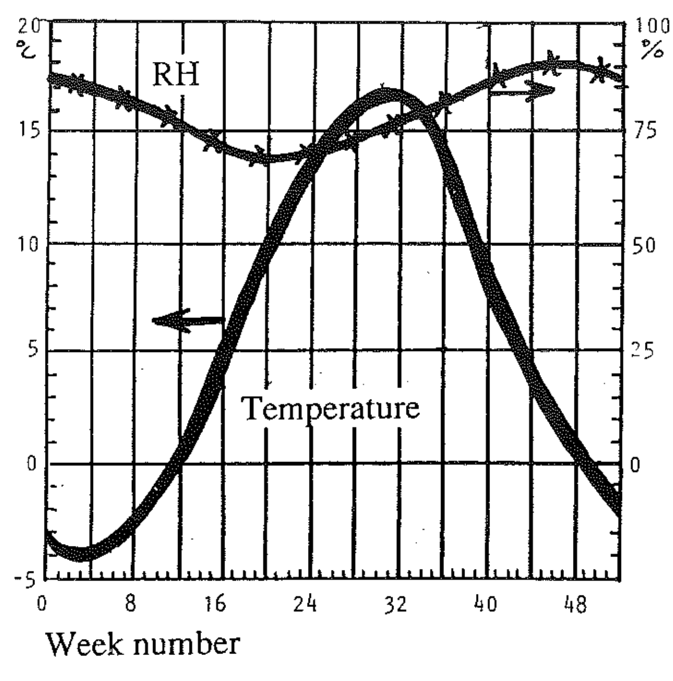

Figure 2 *Temperature and relative humidity in central Sweden over a year.*

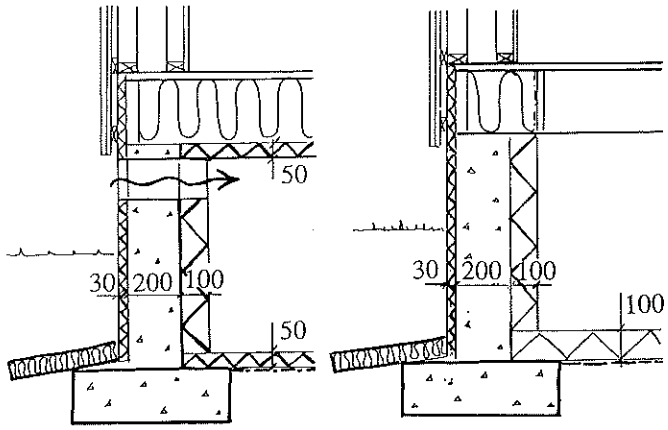

Figure 3 *Schematic representation of the outdoor-air-ventilated and indoor-air-ventilated crawl spaces used in the calculations (Hagentoft 1992).*

space, the temperature varies between 2.3°C (36.1°F) and 13.9°C (57.0°F) and the relative humidity between 67% and 93% during the year. For the indoor-air-ventilated crawl space, the corresponding values are 16.4°C (61.5°F) to 18.4°C (65.1°F) and 43% to 83%. The results of the calculations show that the heated crawl space is considerably warmer and dryer than the outdoor-air-ventilated crawl space. Temperature and relative humidity conditions also vary considerably less.

MEASUREMENTS

Conditions in four different buildings have been investigated, measuring temperature, relative humidity, and moisture ratio over a year.

Vapor concentration was determined by measurement of temperature and relative humidity in the outdoor air, indoor air, and crawl space. Conventional sensors for capacitive measurement of relative humidity, with integral Pt 100 sensors for temperature measurement, were used. Temperature and moisture ratios in wooden parts were measured using Pt 100 sensors, and moisture ratio measurements were made by means of resistance measurement between two electrical contacts. A datalogger has provided an hourly record of measurements. The values recorded by the datalogger were those obtained during the last five minutes of each hour.

Before installing the instruments, they were calibrated in a climate chamber. Measurements were checked halfway through the measurement period, using calibrated instruments. The values shown are those of the calibrated and corrected values.

DESCRIPTION OF THE BUILDINGS INVESTIGATED

Four different buildings were investigated. Three of them had heated foundations, and one had a conventional crawl space with a dehumidifier. The crawl space area varies between 80 and 130 m^2 (861 and 1,399 ft^2).

The Lidköping Heated Foundation

The Lidköping house shown in Figure 5 is a single-story building that rests on a heated crawl space. The heat in the crawl space is also used to heat the building. The joist structure above the crawl space is completely uninsulated, with thermal insulation being applied to the ground beneath the crawl space and to the peripheral walls.

Heating and ventilation of the crawl space is arranged by discharging the exhaust air from the house to a heater in

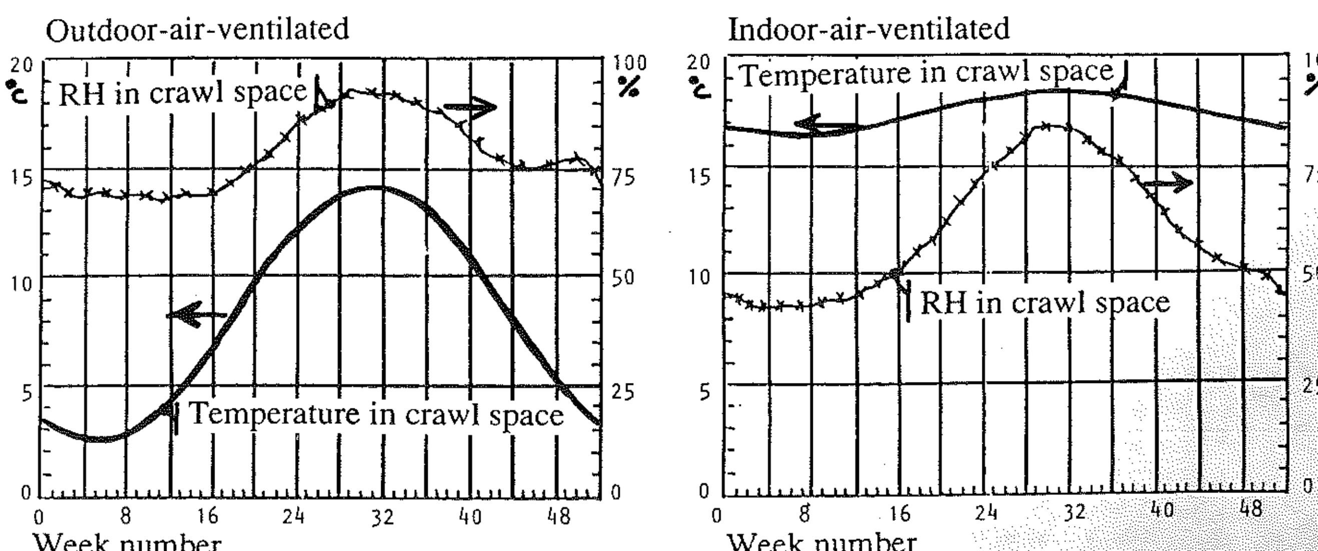

Figure 4 *Temperature and relative humidity in the outdoor-air-ventilated crawl space, with a moisture input of 1 g/m^3, and in the indoor-air-ventilated crawl space, with a moisture input of 3 g/m^3 (Hagentoft 1992).*

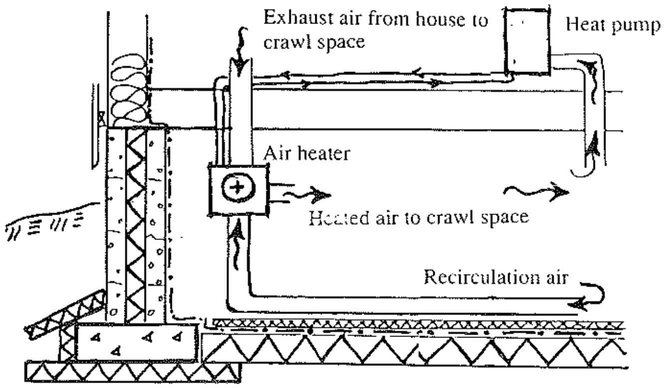

Figure 5 *The heated foundation of the Lidköping house.*

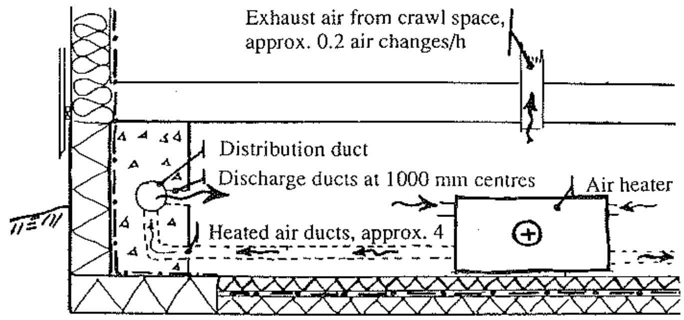

Figure 6 *The Vetlanda heated foundation.*

the crawl space. The heater raises the air temperature to 35-45°C (95-113°F) before blowing it into the crawl space. Heat for the heater is provided by an exhaust-air heat pump. In addition, some of the air is recirculated in order to achieve a higher airflow rate with an even excessive air temperature in the crawl space.

The Vetlanda Heated Foundation

The Vetlanda house shown in Figure 6 is a single-story building. It is set on a heated foundation, the warmth from which is also used for heating the building. The floor structure is uninsulated, with thermal insulation being applied to the ground and to the peripheral walls.

A slight negative pressure is maintained in the crawl space by an exhaust fan. Air from the interior of the house finds its way down into the crawl space through small gaps around the periphery of the external wall. The ventilation air change rate in the crawl space is about 0.2 ach.

Heating and air circulation in the crawl space are provided by a heater installed in the center of the space. Air is heated and discharged via ducts to the perimeter, where ducts cast into the concrete peripheral wall distribute the air to outlets spaced around it.

The Kungälv Heated Foundation

The Kungälv house shown in Figure 7 is a single-story building. It has a heated crawl space, which is also used to heat the building. The floor structure is uninsulated.

The indoor temperature is controlled by means of a floor heating system. Heating pipes buried in the layer of sand on the bottom of the crawl space allow heat to be stored at off-peak times for use at other periods.

This foundation was essentially designed for no ventilation at all, but a fan extracts a modest airflow from the crawl space in order to maintain a slight negative pressure with respect to the indoor air.

The crawl space is heated by circulating hot water through pipes in the layer of sand on top of the foamed plastic insulation. This is done at times of cheap off-peak electricity, i.e., during the night. The layer of sand serves as a heat store, releasing its heat during the day. By starting up the heating system at an early stage of construction, before the floor above the crawl space has been built, the temperature of the layer of sand can be raised and quickly dry out any residual building moisture.

The Hultafors Dehumidified Crawl Space

The Hultafors house shown in Figure 8 is a 1½-story building. It was originally supported on a conventional, outdoor-air-ventilated unheated crawl space, but this was subsequently modified to produce an unventilated crawl space. The floor structure above the crawl space is fully insulated.

The crawl space is dehumidified by means of an absorption dehumidifier. The dehumidifier is installed in the northwest corner of the building, with the air being circulated through it and discharged through a duct to the

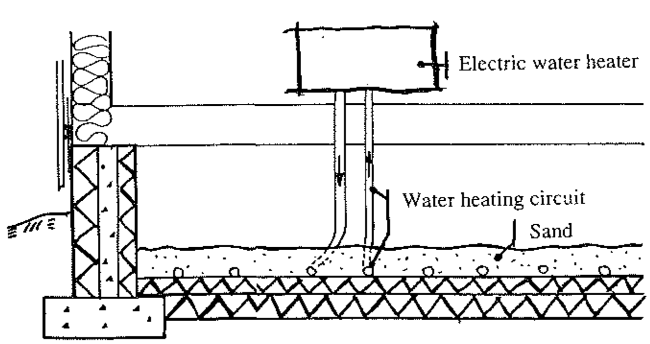

Figure 7 *The Kungälv heated foundation.*

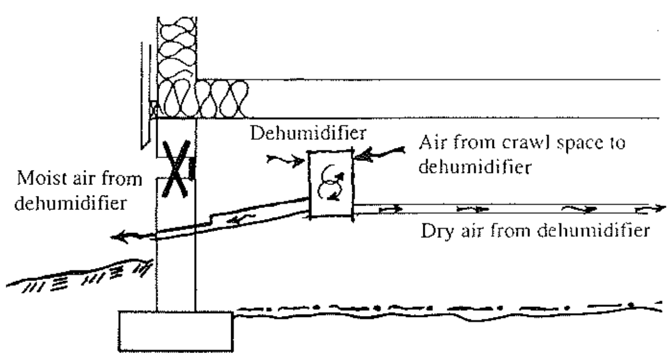

Figure 8 *The Hultafors crawl space foundation.*

southeast corner in order to create a circulating airflow. The air used to regenerate the absorption rotor, i.e., to carry away the moisture collected by the dehumidifier, is abstracted from the crawl space and discharged through the perimeter wall. This also serves to maintain a slight negative pressure in the crawl space.

MEASURED RESULTS

The diagrams in Figures 9-12 show the air temperature, relative humidity, and calculated vapor concentration for the indoor air, outdoor air, and air in the crawl space. The diagrams show a measurement period during the summer.

DISCUSSION

Actual conditions in the three heated foundations differ from the theoretical conditions in that their temperatures are about 5 K (41°F) higher, i.e., 20-25°C (68-77°F) due to additional heat input. This means that relative humidity is also somewhat lower, at a value of about 50-60% during the summer, as against a theoretical value of 70-80%. It is therefore of more interest to investigate the moisture input to the crawl space relative to the indoor air.

In the case of the Lidköping foundation, the moisture input to the foundation space relative to that of the indoor air amounted to about $1.5 \cdot 10^{-3}$ kg/m^3 (1.25 g/kg) during

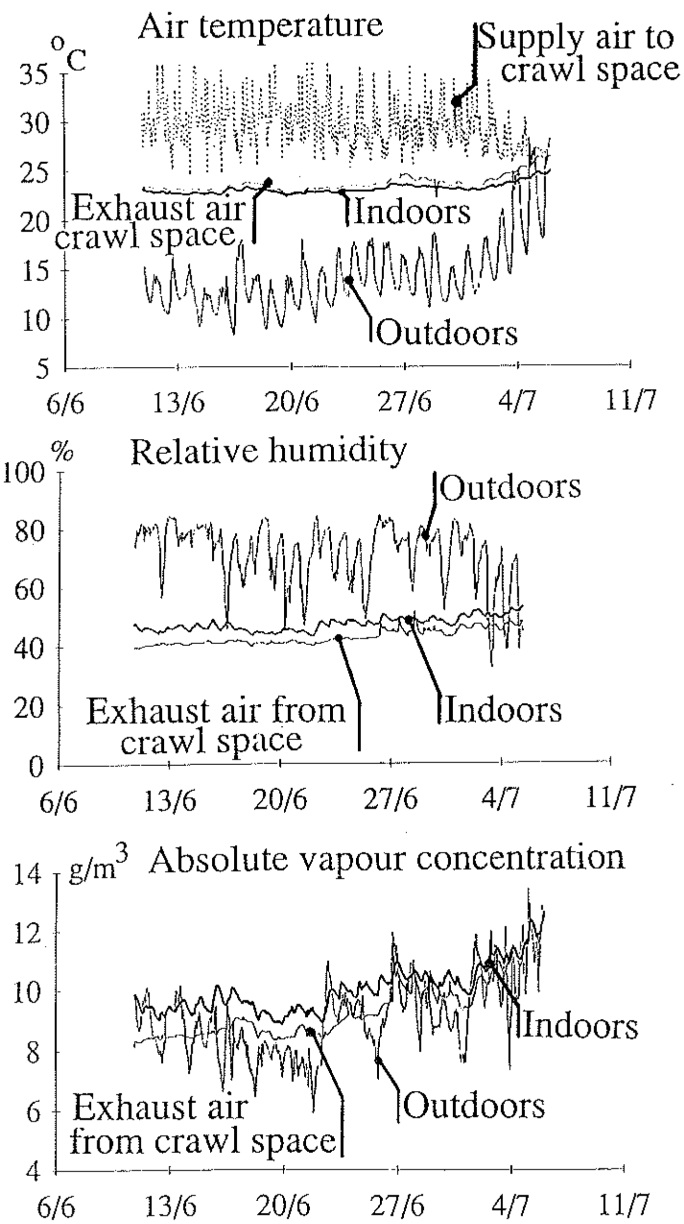

Figure 9 *Air temperature, relative humidity, and vapor concentration in the outdoor air, indoor air, and crawl space air in the Lidköping heated foundation.*

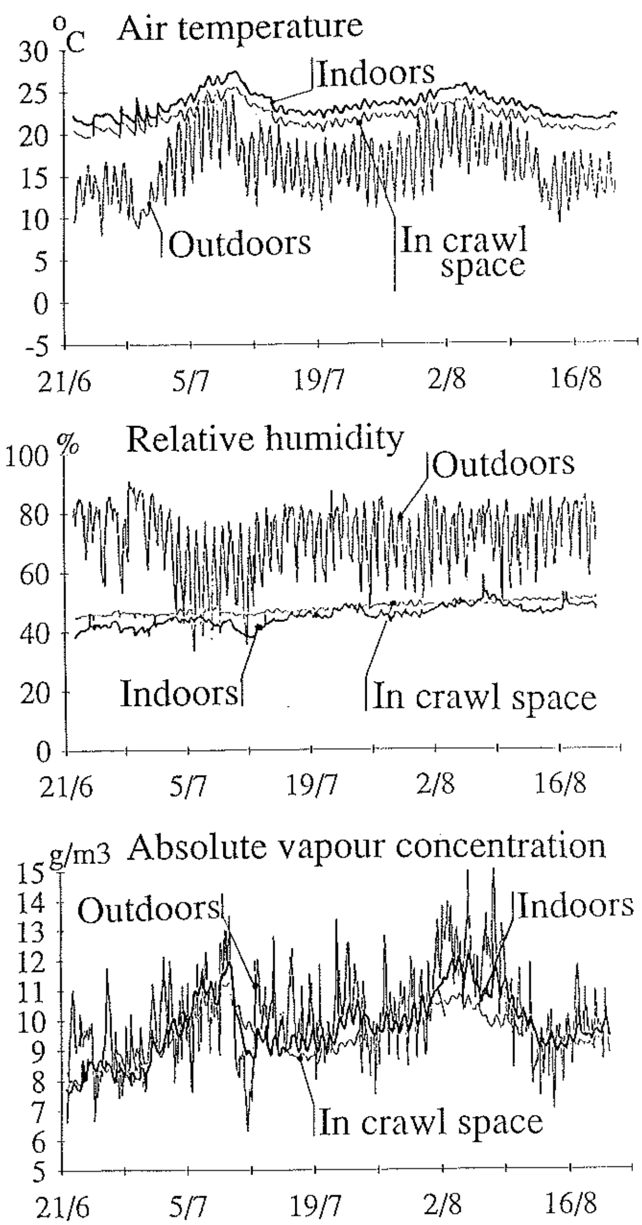

Figure 10 *Air temperature, relative humidity, and vapor concentration in the outdoor air, indoor air, and crawl space air in the Vetlanda heated foundation.*

the early parts of the summer. This difference could be explained by the fact that the indoor air measurements were made in a clothes storeroom. The exhaust air also contained air from the bathroom. The other two crawl spaces exhibit a certain inertia in responding to variations in the vapor concentration of the outdoor air, which is to be expected as the ventilation air change rate in the crawl spaces is limited. Nevertheless, the moisture input in all cases is low.

The results of the moisture ratio measurements, which are not presented here, also indicate the same tendency toward low values overall, of less than 0.15 kg/kg (0.15 lb/lb). An exception was a measurement point in the Kungälv foundation, in the vicinity of which a water leak had occurred. This resulted in the moisture ratio rising in the vicinity of the edge of the floor structure to 0.22-0.24 kg/kg (0.22-0.24 lb/lb). After the water leak had been repaired, the moisture ratio fell within one to two months.

In the fourth crawl space, which is not really a heated foundation at all, the air has been only dehumidified. The absorption dehumidifier has provided relatively good control

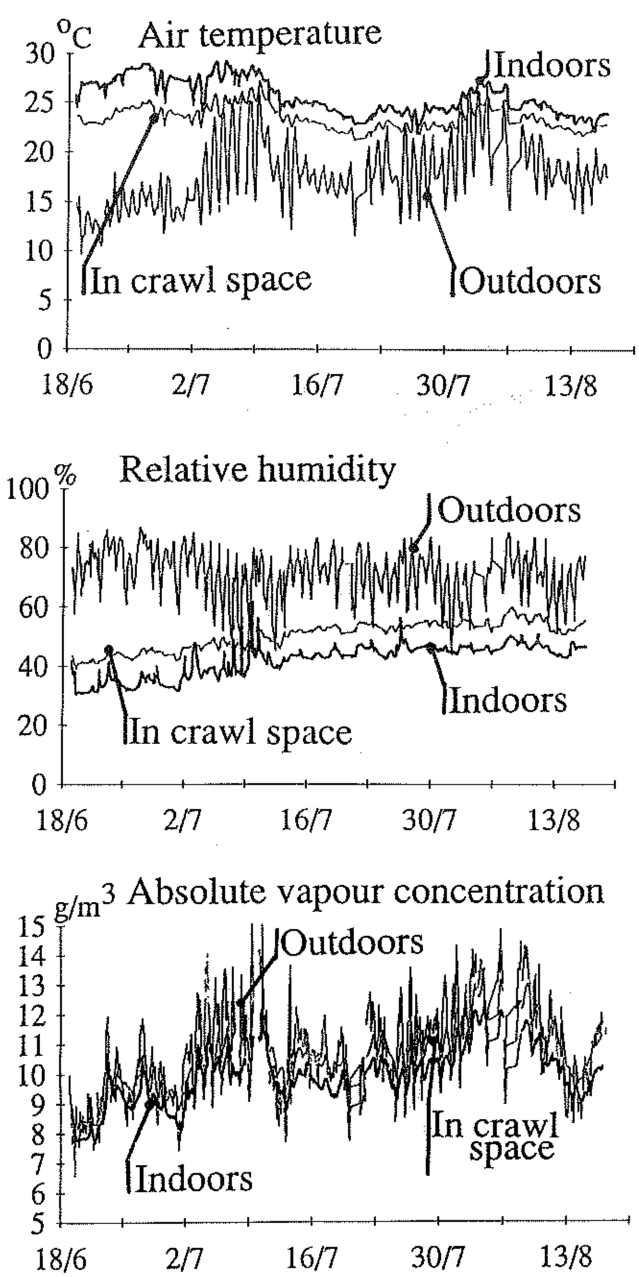

Figure 11 *Air temperature, relative humidity, and vapor concentration in the outdoor air, indoor air, and crawl space air in the Kungälv heated foundation.*

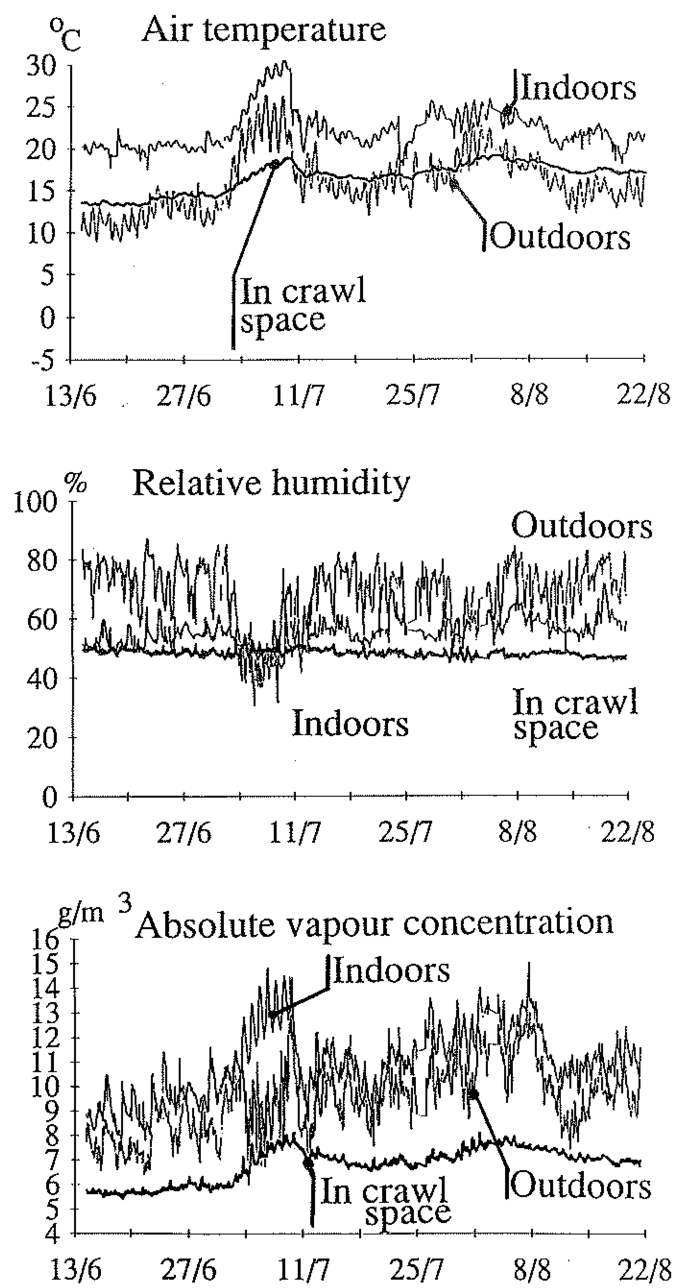

Figure 12 *Air temperature, relative humidity, and vapor concentration in the outdoor air, indoor air, and crawl space air in the Hultafors dehumidified crawl space foundation.*

of the climate to the required level of about 50% RH. During the summer, energy use for dehumidification amounted to about 6-7 kWh per day, reducing to considerably less (about 1.5-2.5 kWh/day) during the winter.

Note that the measured indoor temperatures in all cases should be interpreted with some care, as we had to make our measurements in rooms in the houses that were isolated from day-to-day activities. It has not, therefore, been possible for the measurements to respond to rapid temperature changes resulting from user habits or insulation.

CONCLUSIONS

Both the theoretical calculations and the practical measurements show that it is possible to produce a moisture-resistant foundation having a stable climate throughout the year. This could be done by warming the crawl space provided that it is

- intended to be warmed by provision of thermal insulation against the ground and around the peripheral walls and by the elimination of thermal bridges,
- airtight,
- put under a slight negative pressure.

The risk of mildew growth in the foundation, with resulting risk of the spread of odor to the indoor air, can therefore largely be eliminated.

The measurements that we made also indicate that the foundation design is relatively tolerant to water leakage and residual building moisture. Moisture dries out relatively rapidly.

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