# Activity 1:  Introduction

## Background:

Damage caused by uncontrolled moisture accumulation in building enclosures is of great concern to the construction and energy conservation communities.   Since the introduction of new energy and ventilation standards beginning in 1980s, there has been a great deal of speculation about the effects these standards have had on the hygrothermal performance of buildings. A recent survey conducted by the City of Seattle documented 52 recent moisture related building failures, at a cost of $98 million.  Similar problems have been reported in Minnesota, Boston, Portland, Oregon, Vancouver, and even in Arizona. Concern about moisture accumulation has caused the building industry to be skeptical of new energy efficient construction methods, and has slowed the adoption of new energy efficient building envelopes.  As scientific data/documentation to refute/support the speculations is not forthcoming on either side, misinformation in the building community codes and standards has prevailed.

In Minnesota, the Legislative authority directed the department of Administration, Building Codes and Standards Division to prepare a report by December 2001 on the implementation of the energy code. One part of this requirement provides building envelope systems used in single one- and two-family R-3 occupancy buildings that are energy efficient, enforceable, and provide sufficient non-mechanical ventilation or permeability for a home to maintain good air quality, building durability and adequate release of moisture.  The Building Codes and Standards Division has requested Building Science Corporation to provide a proposal compiling existing theory and research/ documentation of demonstrations on establishing criteria that can be included as part of the report to the legislature.

Category 2 homes (as requested to be included by the Minnesota Legislature) are not permitted under current Minnesota Energy Code, but are allowed under Minnesota Statute 7670.  In these building envelope systems, the interior vapor retarder would not be installed.  The envelope would be permeable, but the homes are assumed to meet ASHRAE Standard 62-1989 without mechanical ventilation.

Since time and resources do not permit further research, the feasibility of such Category 2 homes must be generated with existing theory, knowledge, expertise, and tools. It is the intent of the Building Science Corporation, in collaboration with the Oak Ridge National Laboratory, to present a clear and scientifically documented response to the moisture engineering issue facing the Minnesota Department of Administration, Building Codes and Standards Division.

## Objectives:

The activities proposed will develop required data to determine whether it is feasible to implement either alone or in combination with a permeable envelope, criteria for non-mechanical ventilation which will ensure satisfactory air quality, and envelope durability.

## Overview/Methodology:

This project will assemble information to assess the feasibility of criteria to allow one- or two-family houses with indoor humidity controlled by permeable walls and/or non-mechanical ventilation. As this project intends to determine such criteria, a parametric analysis is required. The approach proposed is to determine the constraints of using permeable systems by quantifying the hygrothermal loads that may be involved in systems with and without permeable envelopes. Similarly, it is important to develop the loads that exist in ventilated and non-ventilated building systems. These hygrothermal loads would be representative of occupant behavior for a specific climate. For this project a few climatic conditions will be chosen within the state of Minnesota, and a multi-year analysis will be performed to obtain conditions that are representative of moisture risk/damage rather than conditions for energy analysis. From the multi-year weather analysis, 10% percentile cold and 10% percentile hot years will be developed for use in the moisture prediction analysis. In addition to existing literature data, building physics expertise is also used to develop insight into the ventilation and moisture issues.

Initially, a set of envelope systems (walls) was jointly selected by the Building Science Corporation and ORNL, and upon approval from the Department of Administration (Mr. Steve Hernick), design inputs were developed. A system engineering approach was used for the selection of these energy efficient wood-framed building assemblies (Lstiburek, 1999). These envelope systems include two types of exterior cladding, different sheathing hygrothermal performance capabilities, and different interior vapor control strategies. The sets of developed envelope systems were used in the parametric analysis to determine feasibility of satisfactory performance. If these walls perform satisfactorily, then feasibility design criteria will be generated.

In parallel, another research activity was conducted by using basic building science principles and a critical review of existing literature data results to generate conclusions. Indeed, the intent of the request for this proposal was to be based on such a qualitative analysis. The integration of both the quantitative and qualitative analysis is important for this work.

In the environmental load analysis, three interior climate classes were developed. From the literature search, natural ventilation building conditions were assigned to two kinds of occupant moisture production rates. These rates were used to develop corresponding indoor air quality conditions. A direct coupling of the building envelope with the interior moisture loads was also simulated using the ORNL holistic hygrothermal model simulator for a limited set of extreme boundary and envelope designs. This activity alone addressed the use of the most appropriate ventilation strategy.

This project examined the function of a number of design decisions that modify existing wall designs by making them more permeable in terms of moisture and air tightness, and the coupled influence of occupant moisture production behavior and the use or lack of mechanical ventilation.

The work needed to accomplish the objectives of this proposal required four activities. The specific details for each of the activities were as follows:

## Activity 1: Literature Review

The first activity conducted a literature search on permeable building envelopes and/or non-mechanical ventilation building performance in climates similar to Minnesota. In this activity, information on measured whole-building characterization, in terms of natural ventilation and/or mechanical ventilation, was assembled and analyzed. Another activity in this task was to identify four wall systems that would be used in the parametric analysis. Four final wall design details were delivered to the Minnesota Building Codes and Standards Division and were approved. These wall systems were delivered close to the project start date (letter submitted 11/28/01; contract signed 11/27/01). In Activity 1, a review of the state of the art in building science is presented. An analysis was performed on the indoor humidity. A report on passive ventilation was reviewed and results were extrapolated for Minnesota conditions.

## Activity 2: Load Analysis

The second activity identified and characterized the important boundary inputs and loads for a selected number of envelope systems. Hygrothermal loads include those due to moisture, temperature and pressure. To develop criteria for permeable and non-mechanical ventilated systems, hourly hygrothermal loads were needed. Loads analysis was performed for both interior and exterior conditions. On the interior side two moisture production rates were investigated, representing families in single one- or two-family residential constructions. Input from Activity 1 provided the needed air change rates for non-mechanically ventilated buildings. Indoor conditions were generated that typify at least one naturally ventilated building, and two with mechanical ventilation. Two locations were chosen within Minnesota (Minneapolis and International Falls). The wall orientations were chosen to maximize the wind-driven loads and air exfiltration characteristics.

### Activity 3: Advanced Moisture Engineering/Modeling

In this activity, the ORNL MOISTURE-EXPERT model (Karagiozis) was employed in developing a parametric analysis of the performance of permeable wall systems without mechanical ventilation. A series of 2-dimensional simulations were performed. The 2-D simulations were used to investigate the hygrothermal effects of infiltration/exfiltration through the envelope walls. In the 2-D simulations, the influence of air flow through the wall system was evaluated, as a function of hourly wind pressures, stack effect, and mechanical pressures. Time constraints did not permit the full simulation results to be included in this draft final report, but will be included in the final report due January 15, 2001.

### Activity 4: Establishment of Performance Criteria

In Activity 4, criteria were summarized from outputs from the above activities. A final report was written to address additional issues such as costs of the wall systems were also included.

## Building Science Basics

## Moisture Control Dynamics

Vapor diffusion is the movement of moisture in the vapor state through a material as a result of a vapor pressure difference (concentration gradient) or a temperature difference (thermal gradient). It is often confused with moisture movement into building assemblies as a result of air movement. Vapor diffusion moves moisture from an area of higher vapor pressure to an area of lower vapor pressure. The movement of liquid often occurs in either direction—either co-current or in the opposite direction, based on capillary pressure gradients. Air transport of moisture will move moisture (predominantly vapor moisture) from an area of higher air pressure to an area of lower air pressure once moisture is evaporated into the air stream.

Moisture in the vapor state moves from the warm side of an assembly to the cold side of an assembly. This type of moisture transport is called thermally driven moisture, or sometimes, solar driven moisture, if the temperature gradient is due to solar radiation. The sun usually provides the greatest temperature drive across an envelope, but normal operation of a building in either hot or cold climates may develop similar temperature gradients. As moisture passes from a high energy state to a lower one, vapor molecules move either by diffusion or by riding the air stream by convection, and may condense on a cold surface. When this occurs the water vapor content of the moisture in vapor phase decreases, but at the same time, the amount of liquid moisture increases by the same amount (i.e., conservation of mass must occur). Cold surfaces may act as dehumidifiers that condense water.

Vapor diffusion and air transport of water vapor act independently of each other. Vapor diffusion will transport moisture through materials and assemblies in the absence of an air pressure difference if a vapor pressure or temperature difference exists. As with liquid transport, vapor diffusion and vapor convection may be moving in the same or opposite direction. The overall flow of moisture will depend on the relative directional flow rates of vapor diffusion movement, vapor air flow movement, and liquid movement.

The flow rates of any of these three components of moisture transport can be controlled and/or reduced: one can control the movement of vapor diffusion by installing a vapor retarder (or a system of materials that controls vapor diffusion); one can control the movement of vapor air transport by installing air flow retarders (or systems used to control the movement of air); and one can control the movement of liquid by introducing capillary retarders or breaks.

The differences in the significance and magnitude of vapor diffusion and air-transported moisture are commonly misunderstood. Air movement as a moisture transport mechanism is typically far more important than vapor diffusion in many (but not all) conditions. The movement of water vapor through a 1” square hole as a result of a 10 Pascal air pressure difference is 100 times greater than the movement of water vapor as a result of vapor diffusion through a 32 $ft^2$ sheet of gypsum board under normal heating or cooling conditions. The quantity of vapor diffusing through a building component is a direct function of the surface area. For example, if 90% of the area of an envelope wall is covered with a vapor retarder, then the vapor diffusion retarder is 90% effective. A punctured polyethylene film with several tears will act as an effective vapor retarder, whereas at the same time it is a poor air retarder.

In practice it is impossible to eliminate all holes and install a “perfect” air flow retarder. Most strategies to control air-transported moisture depends on the combination of an air flow retarder, air pressure differential control, and interior/exterior moisture conditions in order to be effective. Air flow retarders are often utilized to eliminate the major openings in building envelopes in order to allow the practical control of air pressure differentials. It is easier to pressurize or depressurize a building made tight through the installation of an air flow retarder than a leaky building envelope.

Another interesting concept is that the interior moisture levels in a tight building envelope are also much easier to control by ventilation and dehumidification than those in a leaky building envelope. In most building assemblies, various combinations of materials and approaches are incorporated to provide for both vapor diffusion control and air transport moisture control. For example, in cold climates (Minnesota), during heating periods, maintaining a slight negative air pressure within the conditioned space will control the exfiltration of interior moisture laden air. However, this control of air-transported moisture will not control the migration of water vapor as a result of vapor diffusion. Therefore, installation of a vapor diffusion retarder towards the interior of the building assembly is also typically necessary.

In a similar fashion, control of vapor diffusion and air transported moisture in cold climates during heating periods can be enhanced by maintaining the interior conditioned space at relatively low moisture levels through the use of controlled ventilation and source control. Similarly, during the summer in an air conditioning environment, slightly positively pressurizing the interior may prevent the infiltration of exterior hot humid air.

In summary, the performance of a wall will depend on the moisture control dynamics, and well-established building physics can be used to describe the envelope performance.

## Envelope Design Strategy

Building assemblies need to be designed to maintain safe thresholds of moisture in each layer by protecting them from wetting due to air transport and vapor diffusion. The control strategies involve:

- Vapor Diffusion Retarders
- Air Flow Retarders
- Air Pressure Control
- Control of interior moisture levels through ventilation and dehumidification

In cold climates, the heating periods are longer and assemblies need to be protected from getting wet from the interior. Vapor retarders and air flow retarders are installed towards the interior warm surfaces. Furthermore, conditioned spaces should be maintained at relatively low moisture levels through the use of controlled ventilation (dilution) and source control. A degree of forgiveness should be used in the envelope design strategy, and in cold climates, allowing building assemblies to dry towards the exterior. Therefore, permeable (“breathable”) materials should be used as exterior sheathings.

## Previous work on Vapor Control

In a recent paper of William Rose (APT Bulletin), he traced the introduction of vapor barriers in modern buildings. The following information is a summary of the article (Rose, 2001) presented after Westford Symposium V, August 6, 2001. The historical overview was traced as early as the 1920s when the American Association of Heating and Ventilating Engineers (ASH&VE), now American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE), took on the responsibility to examine the thermal and moisture conditions in buildings. Thermal insulation was first used to prevent mold growth in industrial buildings, especially to maintain the stability in the interior environment of paper and textile mills. The use of cork as an insulation material of choice was widespread, and was used to reduce the cold spots on the interior of humidified buildings. One of the first researchers to recognize the need of vapor barriers and air leakage control was Barrett in 1923. By the 1930s, a range of insulations and building papers were available. In 1930, Paul Close argued that insulation develops better thermal control in buildings, but not moisture control.

In the late 1920s, with advent of refrigeration, Dr. Frank Rowley (from the University of Minnesota) recognized the moisture problems associated with insulated refrigeration enclosures and proposed that thermal and moisture flow could be analyzed in an analogous manner. His work was the basis of attempting to understand moisture migration based on diffusive transfer. He recommended cold-side ventilation in frame construction and called for vapor barriers, after conducting a research project with the National Mineral Wool Association. Tessdale at the Forest Products Laboratory applied Rowley’s findings, but he also failed to note the effect of imperfections and workmanship (i.e., air barrier failures) on the use of diffusion theory to resolve all moisture phenomena. It was not until the late 1940s that Britton showed the limitations of the previous work, by witnessing the moisture damage observed with the introduction of crawlspace construction to North America.

In 1948, Dr. Rowley revisited the issue of vapor control, and demonstrated that the introduction of plywood to replace board sheathing increased house airtightness, and thus increased indoor relative humidity and created the need for the new measures of vapor barriers and attic ventilation. Around 1950, a new material, “polyethylene,” was introduced into construction.

In 1950s, Neil Hutcheon from the National Research Council of Canada openly challenged the theory of diffusion as the only moisture transport contributor to moisture induced problems. He put the theory of diffusion to the test using the cold climates in Canada, showing that the measured rate of condensation was 10 times greater than that offered by Fick's theory. Prescriptive measures using simple formulas were found to be imprecise, misleading, or even detrimental to the envelope design. That was the shifting point at last in Canada for consideration of air leakage effects.

According to Rose, it was not until 1980 that US practice began shifting back toward a concern for convective air transport of moisture.

This project intends to investigate the effects (vapor and air transport), coupled with the indoor air quality issues and inhabitant behavior that directly modify the dynamics of the interior loads of the buildings.

## Moisture Control by Passive Ventilation Systems

A report by Casselman was found very applicable to the objectives of this work. The report describes field research conducted in Ottawa, Canada with weather conditions very similar to that of Minnesota (cold climate).

The premise of the work is that control of a building's interior humidity levels can be achieved by two methods. The first and most obvious is to reduce the interior humidity sources and the second one is to maintain the interior at a negative pressure in comparison to the exterior by eliminating exfiltration of moist interior air into the exterior skin of the structure. Any openings from the exterior to the interior can have an effect on the first method of controlling the interior humidity, by diluting the interior air with dry exterior air. However, implementing the second method (eliminating exfiltration) will require a solution more involved than simple openings in a horizontal plane.

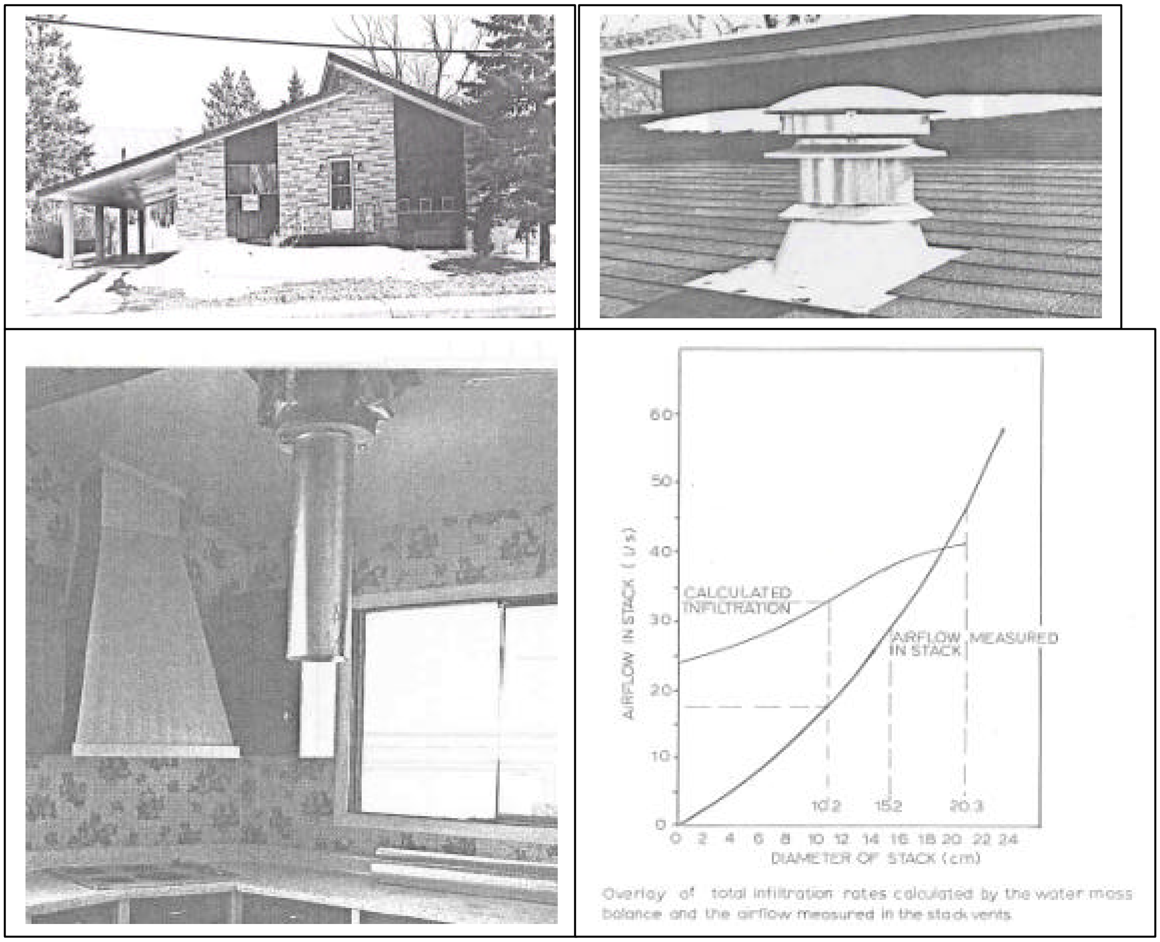
The report proposed natural draft of air via a vertical chimney as a method to create the conditions in which the house is kept under negative pressure, with most infiltration through the exterior skin and most exfiltration up the chimney. Air movement in this manner can positively affect both the interior humidity level and the relative air pressure of the house interior.

The house used in the study was a 1-story bungalow (9.14 m x 12.19 m, or 30'x 40'; 1200 ft$^2$) in size. The above grade and attic insulation was nominally R-11 (RSI 1.94) and rigid foam insulation R-10 (RSI 1.75).

The stack vent installed in the kitchen was a 250.4 mm (9.9") diameter insulated chimney flue, as shown in Figure 1.1. The vent with a 200.3 mm (7.9") insert was used. Make-up air into the house was supplied by natural house leakage as well as by a 100.1 mm (3.9") diameter laundry room vent. Wind-induced pressure effects and stack effects affect the infiltration patterns. The stack vent was installed in an attempt to move the neutral pressure plane above the ceiling level, thus ensuring a negative interior pressure, resulting in predominantly infiltration through the walls and ceiling

The building was equipped with individual room controlled baseboard heaters. Occupant humidity input was simulated using a duct mounted atomizing humidifier. The flow rate of water used varied in the tests from 4 mL/min (1.5 gallons/day) to 16 mL/min (6.1 gallons/day). In comparison, the low and high moisture generation rates used in the moisture models (see Activity 2) were 1.8 & 4.4 gal/day, respectively, which approximated a family of one or two, and a family of four. Various sizes of stack vents were used to determine the relative effectiveness of different sized vents.

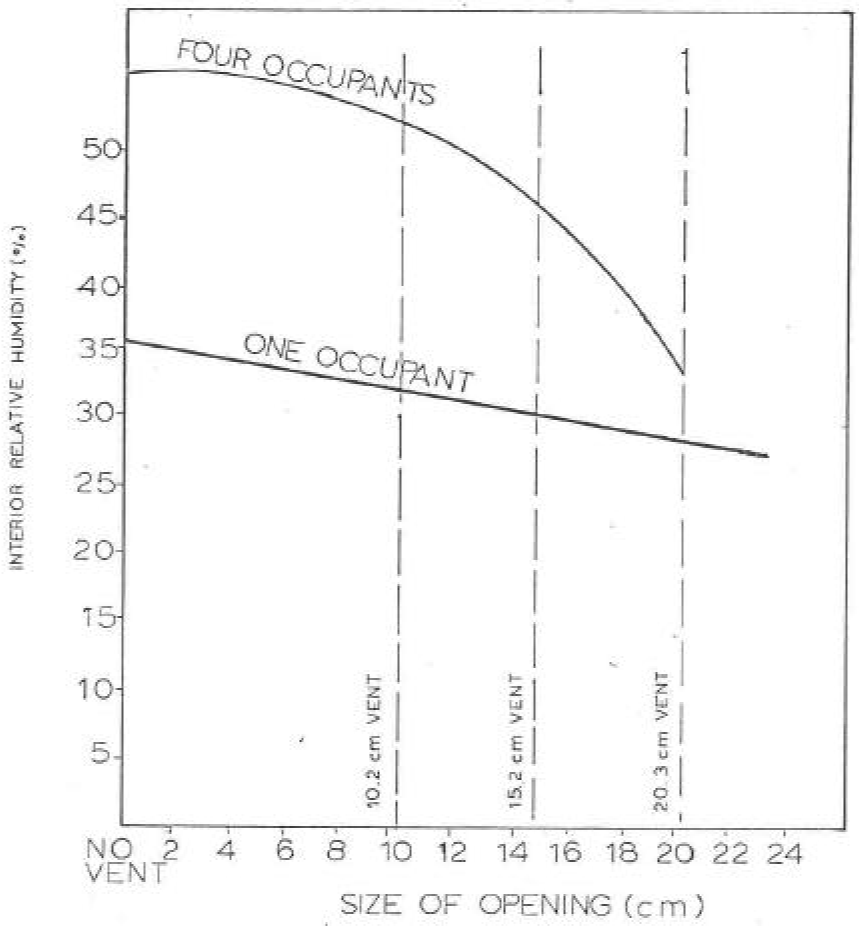
Airtightness tests indicated that the house air change rate was 1.22 ACH at 10 Pa. At 1 Pa, leakage present due to the usual wind pressure difference develops a calculated infiltration estimate of 40 CFM (19 L/s). This value should be adjusted due to increased wind pressure effects during the winter season but is a representative leakage rate for the test period. A hot wire anemometer was used to measure the airflow in the stack vent to determine the air leakage directly through the vent. In the figure below, with the 10.2 cm (4”) stack installed the measured flow air flow was 36 CFM (17 L/s). The 20.3 cm (8”) stack had an airflow of approximately 53 L/s (112 CFM). The data indicate that with the 10.2 and 15.2 cm (4” and 6”) diameter stacks installed, the total exfiltration was greater than the exfiltration up the stack. The air leaving the house left through the stack vent, as well as through the walls. The authors gave the following example: the total infiltration was 32 L/s (68 CFM), and the airflow up the installed 10.2 cm (4”) vent was only 17 L/s (36 CFM). This supported the theory that the smaller vents did not create a negative pressure throughout the house. If the house were operating under a negative pressure with respect to the outside, all of the air infiltrating would have been exhausted by the stack vent. In the case of the 20.3 cm (8”) vent, a negative pressure state may have been prevailing, since the total infiltration was less than the exfiltration in the stack.



Overlay of total infiltration rates calculated by the water mass balance and the airflow measured in the stack vents

Figure 1.1: Casselman Report (House, Vents and Air Flow Dynamics)

In Figure 1.2, the measured reduction in the interior relative humidity is shown as a function of vent size for either one or four house occupants. In the "no venting" case, the interior relative humidity was 57%, but the RH dropped off rapidily with venting. The measurements were conducted in spring and the effect of venting during the critical winter months is expected to be even greater according to the author of the report.



INTERIOR RELATIVE HUMIDITY LEVELS vs
VENT SIZE FOR HIGH AND LOW WATER FLOWRATES

Figure 1.2: Casselman Report: Effect of Passive Venting on Interior Relative Humidity

This report clearly demonstrates the effectiveness of employing passive venting for indoor air quality control in a cold climate. However it did not consider the implications on energy loss due to the natural exhaust of stack venting. Passive venting results in overventilation during cold weather, with resulting excessive energy use. Passive venting results in underventilation during air conditioning periods, resulting in possible indoor air quality issues.

## Air leakage of Minnesota houses

Building Science Corporation has measured envelope air leakage and other data; it was used to size the air leakage characteristics of the envelope systems. Below are test results (air changes at 50 Pa or ACH 50) of Minneapolis, Minnesota area houses in the Building Science Corporation database. Most of these homes are Category 1 homes; tests were performed between Spring 1998 and Fall 2001.

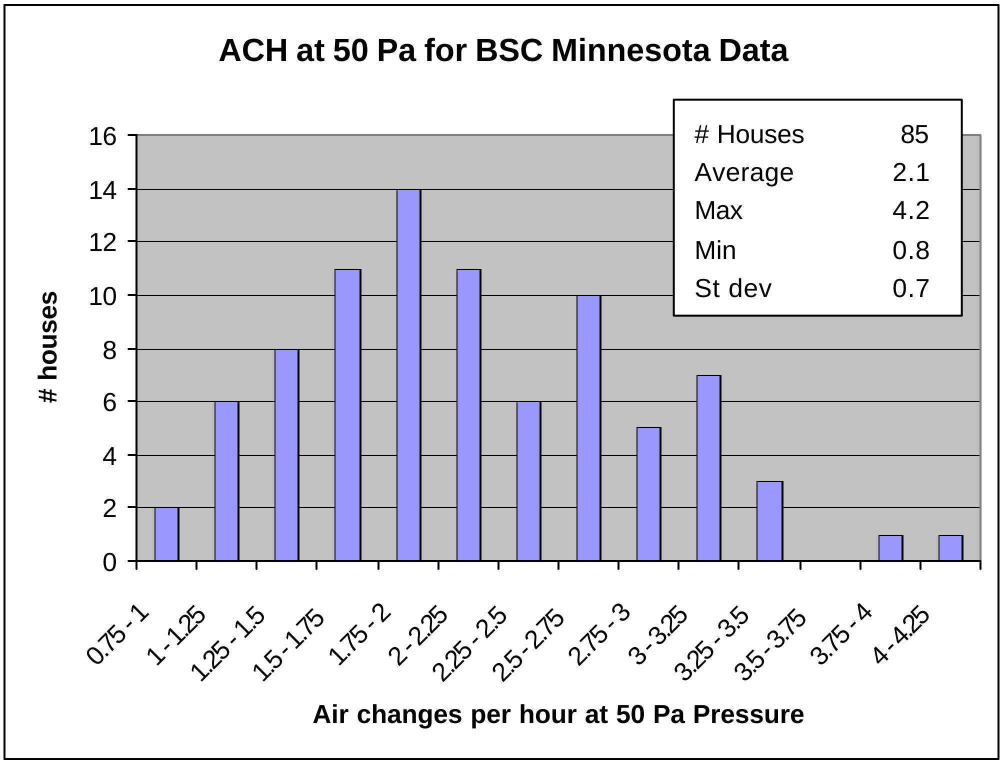


Figure 1.3: Building Science Corporation airtightness test data (85 houses)

Tests dating back to 1994 show that Category 2 homes were 29% leakier than the average Category 1 and 7672 homes.  This coincided well with the recent changes in code language requiring increased air sealing have resulted in tighter buildings.  In a population of about 20 Category 2 homes in Minnesota, more than 12 homes had 3.1 or higher ACH at a 50 Pa pressure difference. In comparison, only 1 Category 1 home, from a population of 17, had a measured leakage value greater than 3.1 ACH at 50 Pa pressure difference.

In the hygrothermal modeling analysis, a value of 4 ACH 50 was used for the proposed Category 2 homes.  Families of 2 and 4 were used, occupying a space of either 1400 $ft^2$ or 2457 $ft^2$

## Indoor air relative humidity

To address the feasibility of criteria to allow one- or two-family houses with indoor humidity controlled by permeable walls or non-mechanical ventilation, the information collected on air leakage performance was used with measured moisture production rates. If the results from this analysis indicate that unacceptable high relative humidity environments occur by natural ventilation, through the permeable walls then this would be detrimental to both the envelope and the occupant. This analysis may satisfy all or a majority the MN code issues that the advanced modeling activity is addressing, in parallel. The simulation results will attempt to model the behavior of the walls when subjected to infiltration/exfiltration airflows.

From the leakage data, the Category 2 home were considered leaky and permeable, and were assigned values of 4 and 5 ACH at 50 Pa pressure difference. One floor size (1400 $ft^2$) was considered. Two occupant moisture production rates were used, as measured by TenWolde and Walker (2001): a low value for one to two adults and the other representing a family of four. In the one or two adult (low) case, the moisture production rate of 6.8 kg/day (1.8 gal/day) was used, while a value of 16.2 kg/day (4.3 gal/day) was used for the family of four. In the analysis, the RH was limited to a maximum value of 70% and a minimum value of 15%. In the analysis proposed by TenWolde and Walker (2001), the effects of moisture storage in the occupied space are neglected and the relative humidity hourly amplitudes are large.

The climate for International Falls was chosen in this analysis. The three years modeled here were the 10% cold year, followed by the 10% hot year, and the 10% cold year. The interior relative humidity results show satisfying ASHRAE ventilation standard of 0.35 ACH requires very low moisture production rates to maintain low enough RH—well below the values produced by one or two adults at 6.8 kg/day.

Figure 1.4 through Figure 1.7 show that unless the air leakage of a permeable home is 0.8 ACH or higher, high relative humidities are present during the moisture critical periods of the year. Vapor diffusion at these interior moisture conditions can cause moisture accumulation in the envelope walls. This, coupled with exfiltration due to stack effect or wind dynamic effects, can cause moisture migration into the permeable wall systems that can cause localized mold envelope damage.

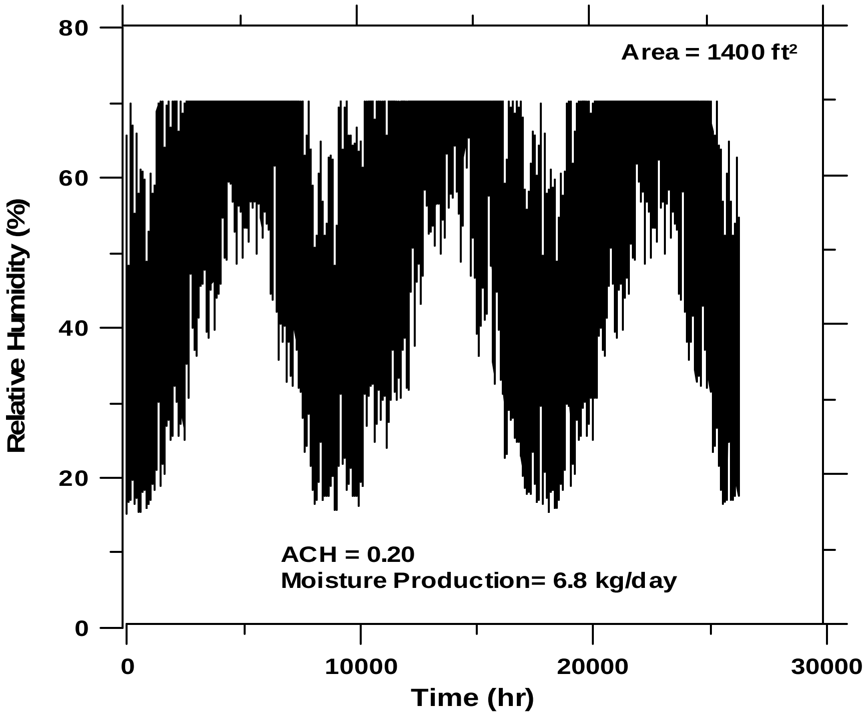


Figure 1.4: Effect of ACH and Moisture Production on Interior RH

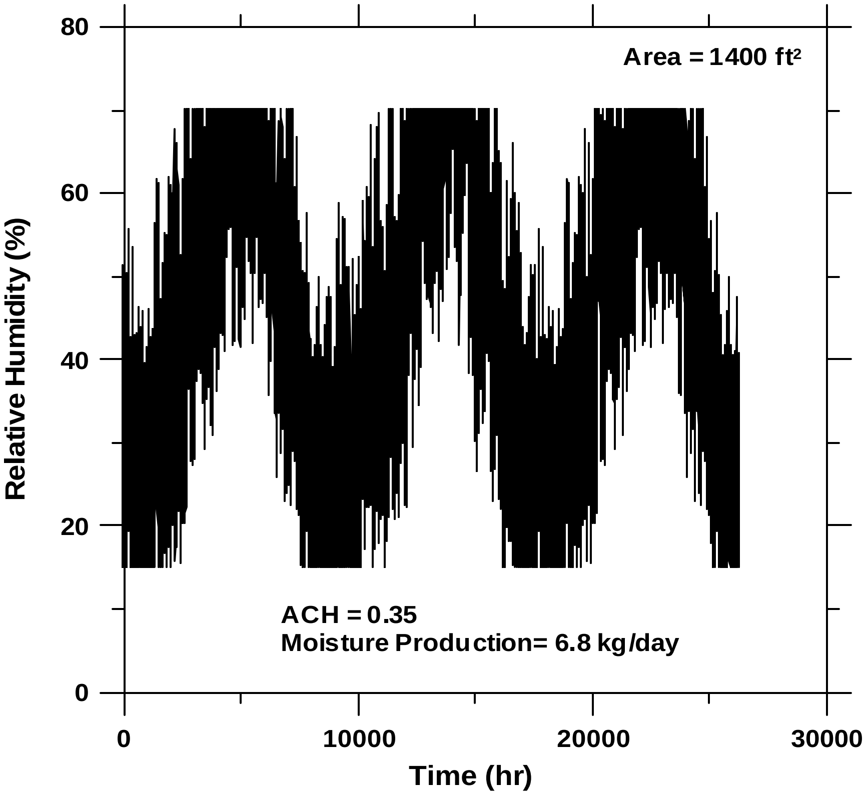


Figure 1.5: Effect of ACH and Moisture Production on Interior RH

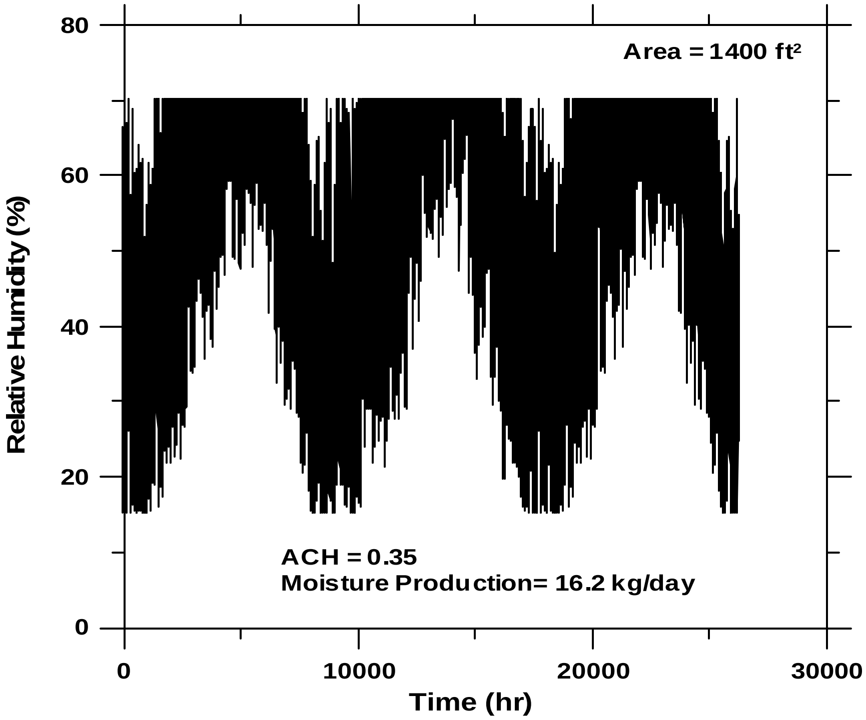


Figure 1.6: Effect of ACH and Moisture Production on Interior RH

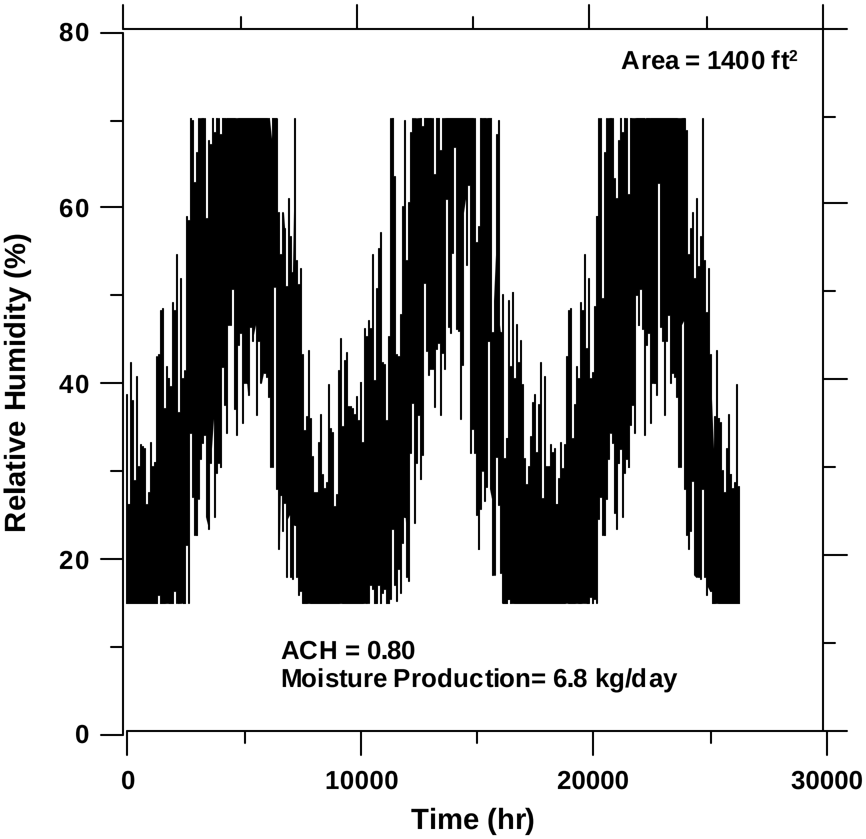


Figure 1.7: Effect of ACH and Moisture Production on Interior RH

## List of Figures (Activity 1)