Achilles N. Karagiozis[1]

Impact of Air Leakage on the Thermal and Moisture Performance of the Building Envelope

ABSTRACT: The air tightness of building envelopes systems is critical to the performance of a building. Uncontrolled airflow movements can cause moisture-induced damage by transporting large amounts of moisture, and may also impact occupant health and safety, sound control, fire control and energy efficiency. Building envelopes are often designed to control airflow by providing a resistance to the bulk flow. Implementation of air barrier systems to restrict airflow is commonly used to reduce the quantity of airflow movement between the exterior and interior environments through the wall.

This paper presents a preliminary assessment of the influence of airflow on the moisture performance of a residential building envelope system. The combined heat, air and moisture (hygrothermal) transport in a selected wall is numerically investigated. Vapor diffusion, liquid transport and temperature dependent sorption isotherms are included in the investigation.

The drying performance of a brick clad wall as a function of vapor diffusion control with a specific air leakage path was studied. The hygrothermal response of the each material layers in the wall subjected to the four climates of Anchorage AL, Boston MA, Madison WI and Miami FL was studied. The effect of different interior environmental conditions and their associated loads on the hygrothermal response of the wall was also investigated.

The MOISTURE-EXPERT hygrothermal model, developed by the author at ORNL, is employed in the investigation. This advanced hygrothermal model incorporates system and sub-system performances by introducing, simulated defects and wall system details derived from laboratory and field measurements. The model also employs temperature dependent sorption isotherms for wooden components.

Results show that air leakage through the building wall system has a significant effect on the hygrothermal performance of the wall. Exterior climate dominates effects of airflow on hygrothermal performance of the envelope. Energy losses were found to be important although measures to accommodate energy conservation by air tighting did not necessary result in a better moisture performance.

KEYWORDS: air leakage, moisture analysis, modeling, brick veneer, vapor retarder, drying potential, moisture transport, hygrothermal performance

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Introduction

A large fraction of the energy consumed for space heating is used to heat ventilation air. Approximately 25 to 40 % of space conditioning energy consumption in well-insulated homes is due to air leakage through the building enclosure. Residential buildings need to be ventilated with outdoor air to maintain acceptable indoor environments. Different ventilation schemes are implemented in buildings to provide the necessary ventilation. Balanced mechanical systems, natural ventilation, dynamic wall ventilation systems, controlled ventilation and exhaust-only ventilation systems are a few methods used. In the cases where ventilation is not controlled, air infiltrates or exfiltrates through the building envelope at unintentional openings around the sill plate, cracks through the wall, at the basement footing and at the first floor and subsequent floor connections, plumbing stack, electrical service conduits, at openings for heat and cooling ducts, and at window/wall junctions. Infiltration can contribute significantly to the overall heating or cooling load of a building and is directly dependent on environmental loads, envelope design and operation, and construction workmanship. Uncontrolled infiltration/exfiltration is a common in residential buildings and influences the indoor air quality, building energy consumption and durability of a building. Of the three above listed impact areas of infiltration/exfiltration airflows, the least understood is the influence on the durability (hygrothermal influence), followed by the influence on thermal performance.

Objectives of Present Study

In real wall systems, some amount of air leakage will be present. This work is concerned with the drying/wetting potential of a brick veneer wall with construction moisture subjected to air leakage. The heat, air and moisture performance of the wall is investigated as a function of two selected interior moisture load environments, and four exterior climatic conditions. The work also investigated the influence of pressures developed by the operation mechanical ventilation system/fans/driers on the wall's moisture performance.

The objective of the work is to determine the hygrothermal performance of the brick veneer wall for the combined air leakage control and interior environmental conditions using a state of the art hygrothermal model that does not have some of the limitations of the previous studies. The modelling analysis was performed while subjecting the exterior boundary to "*real*" weather data (including temperature, vapor pressure, wind speed and orientation, solar radiation, sky radiation, and cloud indexes). Ideally, laboratory and field air leakage data would have complimented the results, but these were not included at the present time. The weather data used are representative of actual extreme, cold mixed and hot and humid climates found in various areas of the United States (Boston, Madison, Anchorage and Miami). The questions to be answered by this study are:

a) How does the base wall perform in each of these different climates in terms of both energy and durability (context of moisture performance) ?

b) What is the influence of interior moisture load on the hygrothermal performance of the wall ?

c) What is the influence of air leakage on wall performance ?

d) What are the energy implications?

Thermal Performance

Claridge, D.E. and Bhattacharyya [1990] underlined the fact that " a great deal of work has been devoted to the prediction and measurement of infiltration rates in building systems, but little effort has been directed toward determining the actual energy impact of infiltration". To prevent and control the possible air leakage through buildings, air barrier systems (weather resistive barrier systems) are employed that avert excess ventilation and the associated energy costs. Airflow control is provided by an assembly of materials, systems, that include influences from each joint, seam and penetration [Burnett 2000].

An alternative design option is to control air leakage by designing a dynamic wall that encourages ventilation air to flow through the insulated segments of the walls. To utilize this approach the interior is often maintained at a lower pressure than the outside (negatively pressurized) during the heating season and (positively pressurized) during the cooling season. Heat is transferred from the wall to the incoming ventilation air and the air that enters the interior space is at a warmer temperature than the outside during the heating season. The building envelope wall system is strategically designed as a heat exchanger for the infiltrating air. The success of this principle relies on the level of control and air distribution management. The major challenge in this approach is to implement a uniform air flow management systems, for low cost high energy efficiency recovery.

Extensive analysis of the effect of air flows on the thermal performance of walls was performed by Buchanan and Sherman [1998]. CFD simulations were performed in both 2-D and 3-D, and the authors found heat recovery for small air infiltration rates and long leakage paths can be substantial, in some cases well over 80 % . As those conditions are not typical of existing residential stock, the authors estimated that the heat recovery for a typical building could be as much as 40 % . For leaky buildings , the heat recovery was found to be sizeable at approximately 20 %. In addition the authors showed that the 3-D simulations gave nearly the same values as the 2D simulations, in terms of heat recovery and suggested that it could be sufficient to employ 2-D simulations to study the wall performance. Caffey [1979] field investigated several buildings and measured up to 40 percent of the heating/cooling costs in residential homes could be attributed to infiltration. Persily [1982] stated that about one-third of the heating/cooling requirements are due to infiltration. In a paper by the author, Morrison et al [1992], a sensitivity analysis was performed on several wall design parameters. The dynamic ventilation effectiveness was examined as a function of flow rate of air through the wall, insulation thickness, location and size of openings. In addition, climatic variables that were considered in the analysis were ambient temperature, air pressure and absorbed solar irradiance. The results showed that the size of the orifice at the inner side of the wall is inconsequential, while placement had a moderate impact. Maximizing the solar absorption was found to considerably enhance thermal performance. The dynamic efficiency reported ranged between 13.6 % with no solar radiation to 79% with solar radiation of 400 W/m^2. Dynamic walls were found to have the potential to act as passive solar collectors for ventilation air. Dynamic wall efficiency is defined in a similar manner as Langlais and Arquis [1987] as the fraction of ventilation and wall transmission losses saved by the dynamic action:

$$f = 1 - \frac{q_{dynamic}}{q_{standard}} = 1 - \frac{-k\left(\frac{\partial T}{\partial x}\right)_{dynamic} + \frac{V_{air}}{A_{wall}}\left(\rho C_p\right)_{air}\left(T_{in} - T_{out}\right)}{-k\left(\frac{\partial T}{\partial x}\right)_{standard} + \frac{V_{air}}{A_{wall}}\left(\rho C_p\right)_{air}\left(T_{in} - T_{out}\right)} \qquad [1]$$

Where the $q_{dynamic}$ is the heat loss in W/m2, $q_{standard}$ is the heat loss from a wall without air flows $-k\left(\frac{\partial T}{\partial x}\right)_{dynamic}$ and $k\left(\frac{\partial T}{\partial x}\right)_{standard}$ the heat fluxes from the outer surface of the dynamic and standard wall respectively, V_{air} is the infiltration rate for the house in m3/s for dynamic homes, A_{wall} is the total dynamic surface area of the walls, $\left(\rho C_p\right)_{air}$ the product of the density and specific heat for air, T_{in} is the interior temperature and T_{out} is the exterior temperature. The efficiency f represents the reduction in heating load relative to a wall without infiltration, that has no thermal coupling between transmission losses and ventilation. Air enters the living space at outdoor temperature. The standard wall here does not represent an actual wall as some thermal coupling always exists between the envelope and infiltrating air exists. The main limitation of the study was that the work was performed with static boundary conditions that did not vary as a function of time.

Air Tightness and Ventilation Control Concepts

Ventilation is an important process in buildings because of its impact on both energy requirements and indoor air quality. Both topics are of concern to building envelope designers. Indeed, the air leakage of a building component may differ substantially if tested in the lab or measured under field conditions. Dynamic conditions exist in field conditions, and air leakage performance is a function of various driving forces, and environment. A recent paper by Straube [2001] describes the basics of air flow, the forces driving the flow, and strategies for controlling flow caused by alternative mechanisms such as wind washing, natural convection, internal stack effect and cavity pumping. Driving forces include wind, stack effect and the operation of the mechanical air handling equipment and appliances (clothes dryers, range hoods, exhaust fans). The importance for air flow control was stressed and a complete re-evaluation of the way architects and building envelope specialists design and implement air barrier systems was introduced.

Any meaningful understanding of air leakage requires quantitative measurements using blower doors, micromanometers. The air leakage of a building can be evaluated by using the equation:

$$Q_{50} = C\,\Delta P^{n}$$

where Q_{50} is air leakage (l/s) at 50 Pa pressure difference, C the flow coefficient (l/s Pan), ΔP the indoor-to-outdoor pressure differential (Pa) and n the flow exponent (-). Air leakage rates on both residential and commercial buildings have been reported as Normalized Leakage Rate at a pressure differential of 50 Pa or 75 Pa. This can be written as:

$$NLR_{50} = \frac{Q_{50\,Pa}}{A_{Envelope}}$$

where $A_{Envelope}$ is the building envelope area.

Another way to express air tightness is to use house leakage ratio: the air leakage (cfm50) divided by the adjusted floor area (square feet). A house is considered to be overly tight, requiring continuous ventilation, if the air leakage ratio is less than 1.0. CEE has found that approximately 25% of the homes tested are too tight and require some type of mechanical ventilation system.

Moisture Performance

Air leakage is essentially controlled by an air barrier system; design of an air barrier system is based on a limitation of moisture transport; walls with condensation from air leakage have a failed air barrier system. Air leakage can be a dominant factor in the transport of heat and moisture through building envelope systems[BSI, 1996 (Lux and Brown)]. Deterioration of envelope systems can in many instances be attributed solely to the moisture transported by air leakage [BSF, 1983].

In cold climates (Anchorage, Madison, Boston), interior conditions normally have higher vapor pressures during most of the year than the exterior. The opposite is true for hot and humid climates such as Miami. Depending on the effect of stack pressures, interior mechanical pressures and wind pressures, positive or negative pressure differentials can exist between the inside and the outside of the envelope. The presence of air pressure differentials drives quantities of air through intentional and unintentional openings (cracks). Depending on the temperature distribution and the air passage routes through and around the various material sections in the envelope, moist air can condense. This accumulation of moisture due to air leakage can be many times more important than the vapor accumulation due to diffusion transport. Experimental work detailing the air flow paths within walls has not yet been developed and information is generally lacking. Information regarding the hygrothermal performance of wall systems due to air leakage is limited for cold climates by Ojanen and Kumaran, [1992] and Kohonen, and Virtanen, [1987].

Brick veneer systems, as the one studied in this paper, are one of the most popular exterior building envelope cladding systems in the residential and commercial construction market in North America. A limited number of studies exist that have investigated the effect of air leakage through building envelopes on the moisture performance of walls. Brick veneer systems are forgiving systems in terms of moisture performance, but this cladding system can also be associated with certain durability problems. A combination of air flows and inward vapor drives in brick veneer systems have been reported by Straube [1998] in cold climates. Moisture problems ranging from high moisture content in the exterior sheathing to total rotting were uncovered. The problems developed because moisture did not dry out quickly enough. Questions were raised about the combined effect of interior vapor control strategy and air leakage on the drying of the walls.

Other than the direct work of Karagiozis and Salonvaara [1999] and of Salonvaara and Karagiozis [1998] on exterior Insulation Finish System walls (EIFS), information is not readily available that examines the influence of air leakage on the combined heat and moisture transport. These studies accounted for liquid transport but did not represent liquid uptake and redistribution properly. Previous studies conducted by Kohonen and Vittanen [1987], and Ojanen and Kumaran [1996] are also of limited value in terms of providing moisture performance analysis. These studies used hygrothermal models that did not account for liquid accumulation and redistribution (suction isotherms). Capillary transport and temperature dependent sorption isotherms were ignored.

Material property determination

A serious limitation of hygrothermal modelling is limited availability of verifiable hygrothermal material properties. Accurate hygrothermal material properties for North

American construction materials are not readily available, and for some materials non-existent. The WUFI-ORNL/IBP [Kuenzel et al, 2001] database, specifically the Institute fur Bauphysics material properties database, provides a reliable database of hygrothermal properties. Additional material properties were collected by approaching individual manufacturers. As this paper is concerned with the performance of brick veneer walls to specific parameters, representative materials were used. The basic material properties required in the modelling analysis were:

- Water vapor permeance as function of relative humidity
- Liquid diffusivity (Uptake and Redistribution)
- Sorption as a function of temperature and the Suction Isotherm
- Thermal Conductivity, Density and Heat Capacity

Description of the Hygrothermal Model

The MOISTURE-EXPERT 1.0 hygrothermal model was used in these simulations [Karagiozis, 2001]. This state-of-the-art model was developed to predict the 1-D and 2-D heat, air and moisture transport in building envelope geometries. The moisture transport potentials are vapor pressure and relative humidity, temperature for energy transport, and temperature and pressure for air transport. The model treats vapor and liquid transport separately.

MOISTURE-EXPERT 1.0 model includes porous air flow through insulation and cracks by solving Darcy's equations. MOISTURE-EXPERT model accounts for the coupling between heat and moisture transport via diffusion and natural and forced convective air transport. The model includes the capability of handling internal heat and moisture sources, gravity driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and sub-system performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature dependent sorption isotherms, and directional and process dependent liquid diffusivity.

Problem Description

The hygrothermal performance of a brick clad wall (Figure 1) was analyzed. A brick veneer wall was selected for the numerical analysis. An opening of 1 mm was used on the inside to represent an air flow opening. The opening was assumed to form a continuous cracks across a 1 m width of the wall. This case represents a possible air gap present when the drywall is employed as the air barrier system. A calculated air flow rate of 0.53 L/(m^2.s) is present when a static pressure difference of 75 Pa is applied to the brick clad wall. In the work of, Ojanen and Kumaran [1992] rather large air gaps of 20 mm were employed at the interior wall face, which developed a flow rate of 0.98 L/(m^2.s) employing a 10 Pa pressure difference. Small gaps (1mm) such as the one employed in this study are more realistic than those of 20 mm .

The opening provided the main path for air leakage through the wall system. No direct water entry through these openings was permitted. However, rain water could diffuse at exterior surface of the brick. The wall is centrally located in the middle of a 1-storey building and is composed of the following layers from the exterior to interior: 100 mm brick veneer, 19 mm air space, a 60 minute building paper, 12.5 mm oriented strand board, 89 mm Fiberglass insulation, 6-mil poly, and a 12.5 mm painted gypsum board.

The oriented strand board moisture content was assumed to be in equilibrium at 96 % RH initially. This represents wet initial moisture conditions in the OSB that would be above acceptable moisture content permitted by building inspectors. However, this condition can be present when the OSB is wetted directly by rain. All other layers in the wall system were assumed to be in equilibrium at 83 % relative humidity. Table 3 displays the combinations of the simulations performed. The interior mechanical pressures were extracted from measured values, for the first pressure schedule case and doubled for the second case. Both operated on a 24 hour schedule, with 8 hours of mechanical system operations.

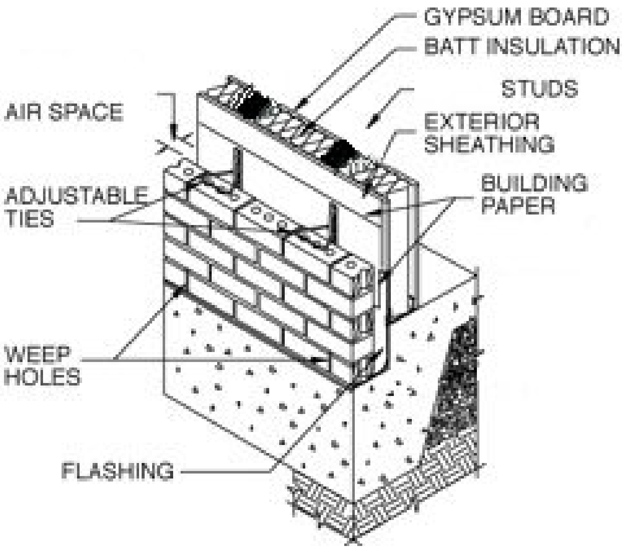

Figure 1: Basic Brick Veneer Wall

Boundary Conditions

The wall was exposed to outside air temperature and the relative humidity that varied according to the hourly weather data from Anchorage, Madison, Boston and Miami. The weather years selected were specifically chosen for moisture calculations Karagiozis [2001a]. The solar radiation absorbed and long wave radiation re-emitted from the outer surfaces of the wall were included in the analysis. The simulations were carried out for a one year exposure (365 days) starting on the 1st of October. In Table 2, the average monthly temperature and average monthly rainfall are given for all climatic locations selected. In Figures 2a through 2h, the wind and precipitation rose diagrams are given for Anchorage, Madison, Boston and Miami. This data was developed from 5 years of hourly data and clearly show the dominant directions for wind-driven rain and air leakage flows. In addition to the wind and rain direction those diagrams show, the rain and wind magnitudes along with the percentage of the time that these conditions prevail. The brick veneer wall was always south facing, Figures 2a through 2h show that this orientation was generally the most critical one. It is important to characterize the dominant influence that orientation plays on the moisture performance of walls.

Two different interior conditions were imposed representing a lower and upper bound. One assumed no internal moisture was generated, while the other condition had a continuous supply of moisture at the rate of 0.001 kg/m^3/hr. This value represents conditions that were determined by analyzing recently measured indoor data from Seattle. Figures 3 and 4 display the imposed hourly relative humidity for a period of a year for each of the four selected cities. The relative humidity as a function of time, starting from October 1 without internal moisture generation is designated as RH_low. For the rate of 0.001 kg/m^3 it is designated as RH_High.

Table 3: Simulation Set-Up Details

Simulations	Parameters				
	Indoor Conditions		Mechanical Pressure		
Anchorage	RH_high	RH_Low	No Mech. Pressure	2*Pressure Schedule (High Pressure)	No Air
Madison	RH_high	RH_Low	No Mech. Pressure	2*Pressure Schedule (High Pressure)	No Air
Boston	RH_high	RH_Low	No Mech. Pressure	2*Pressure Schedule (High Pressure)	No Air
Miami	RH_high	RH_Low	No Mech. Pressure	2*Pressure Schedule (High Pressure)	No Air

Simulation Results

In Figures 5 and 6 the 2-D spatial temperature and relative humidity are presented. Results are shown at one time during the steady state analysis performed to determine the air leakage flow through the wall. A pressure difference of 75 Pa was imposed across the wall. The air paths through the wall are displayed. A distinct two-dimensional thermal and moisture distribution is present in the wall system. This is due to a combination of both natural and forced convection, and this is more obvious in the fibreglass layers. The relative humidity distribution in Figure 6 show relatively high moisture conditions in the OSB layer and the top and bottom wood plates.

In Figure 7 the total amount of moisture present in the OSB layer as a function of time is presented to show the relative hygrothermal performance of the wall for the five different conditions shown in Table 3. Results are shown for the city of Anchorage. The simulations start from the first day of October and results are shown for a period of a year. Results show that airtight wall case (no infiltration/exfiltration) with a vapor retarder allowed dying to occur during the heating season but also accumulated moisture soon after the summer season. The low interior moisture load case clearly shows the most rapid initial drying out potential. This occurred even during the winter period, and performed the best in terms of moisture management with the exception of a two month period. For the three cases with the same RH_High conditions but with different mechanical pressure conditions results show a net accumulation from one year to the next. The effect of air flow has a serious detrimental effect on the hygrothermal performance of the walls, supplying moisture to accumulate in the OSB layer. The prescribed initial moisture content started out already high, in equilibrium at 96 % RH. The fastest drying among the three pressure conditions, was the case without any mechanical pressure, followed by the case with the prescribed mechanical pressure schedule, and the worst condition the one with 2 time the mechanical pressures imposed on the inside. Air leakage increases the drying of the OSB sheathing with this particular wall assembly only when the interior relative humidity is maintained at low levels during the winter season. Furthermore, the results clearly indicate that all materials must be installed dry, as the wall system exhibits slow drying for all cases. For the air tight wall that employed a vapor retarder, outward drying occurs if the structure is air tight.

Figure 8 displays the influence of air flow on the energy performance of the wall system. Here the weekly averaged heat flux of the case with air flow (RH_high) is subtracted from the case with no air and then divided by the heat flux of the no air case giving the percent difference in heat flow due to the presence of air movement in the wall system. Maximum differences of approximately +/- 10 % are found. Negative differences mean that the heat flux from the wall with air flow is higher than those from the no air flow cases. Over 60 % of the time during the year, differences of approximately +/- 4 % are present. These differences for the cold climate used in this part of study show that there is a coupling effect between that may contribute positively or negatively to the conduction losses of the wall.

Figures 9 and 10 show the moisture and thermal performances of the wall for climatic conditions of Madison WI. Figure 9 is similar to Figure 7 for Anchorage. The transient moisture profiles are in the same order, with the characteristic yearly moisture accumulation for the cases with air flow. The only differences found for the Madison cases, the differences between them was now less pronounced. This is directly related to the average mean temperature which is higher than for Anchorage. Figure 10 shows the effect of air leakage on the thermal performance of the wall. With the exception of a spike during summer (where the heat fluxes are very small and the % differences can then become very large), the average percent additional heat flow is approximately 4 %. The influence of air leakage is now less pronounced as in the case of Anchorage.

Figures 11 and 12 show the thermal and moisture performance for the wall located in Boston. The transient moisture distributions show that greater hygric stresses are present in Boston as the wall accumulates more moisture than Anchorage, but it also dries out to a much lower level than both Anchorage and Madison. The main reason for this behavior is that Boston is the warmest of the three cold climates investigated. In addition, Boston also receives considerably more wind driven rain than the two other locations. The differences among the various pressure conditions are less important. In terms of thermal performance, Figure 12 shows that air leakage can contribute approximately 5 % additional heat flux loss.

Figures 13 and 14 show the moisture and thermal performance predicted for the brick veneer wall in Miami FL. This climate is hot and humid with high amounts of wind-driven rain present. All walls dry significantly with the exception of the airtight wall. The higher the interior pressure levels become, the drier is the OSB layer. Since the interior air was conditioned, as it exfiltrated through the wall it warmed up and its potential to accumulate moisture within the wall diminished.

CONCLUSIONS

This preliminary study assessed the effect of air leakage for one air flow path and one wall orientation. No rain water penetration was simulated, as the study focused on the drying potential of a wall system with initial construction moisture. This study investigated a limited set of wall parameters that influence the drying performance of a brick clad wall. Air leakage through an brick clad wall in Anchorage, Madison and Boston, was found to produce a moisture net accumulating effect for a wall system with an initially wet OSB layer. The amount of air leakage passing through the wall was affected by different mechanical pressures imposed in the simulation and was found to influence the drying rate of the wall. Vapor diffusion produced insignificant drying of brick clad walls for cold climatic conditions as well as hot and humid climates.

Drying rates of the brick veneer wall are controlled by the water vapor permeance properties of all critical layers of the wall system, exterior brick cladding, OSB layer, insulation layer, vapor retarder, and interior paint coating. Drying due to air leakage occurred mostly towards the outside.

Further research is recommended to determine the critical range of interior climatic conditions that owners of buildings must adhere to. While air leakage may be beneficial for the drying out of this particular wall system in the low interior relative humidity scenarios, there is an associated energy cost. These costs ranged between 10 % and 5 % for Cold climates and 10 % for hot and humid climates.

Different air leakage paths could influence both the energy and moisture performance of the wall and this is recommended for a further study. The results provided in this paper are only applicable to the specific materials, initial conditions, air flow paths, wall orientation, wall specifications and weather conditions employed. More research is needed to address a full parametric investigation of various wall system with regard to the drying performance of wall systems in North American Climates.

Acknowledgment

The authors of this paper would like to extend sincere thank to Mr. Arun Vohra, DOE Manager for his support of the moisture control program at the Oak Ridge National Laboratory.

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TABLE 1: Average Temperature and Rainfall

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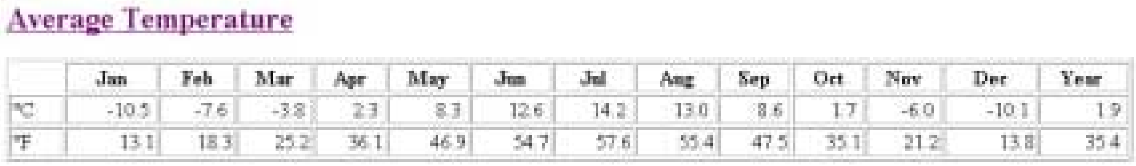
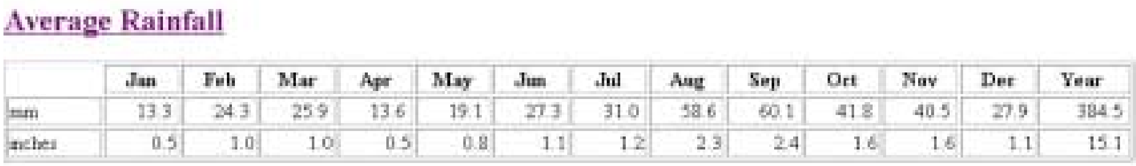


Average Temperature

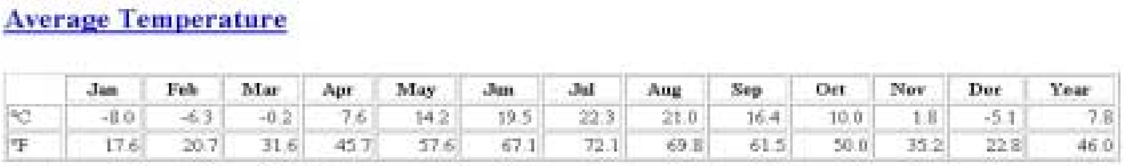
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	-10.5	-7.6	-3.8	2.3	8.3	12.6	14.2	13.0	8.6	1.7	-6.0	-10.1	1.9
°F	13.1	18.3	25.2	36.1	46.9	54.7	57.6	55.4	47.5	35.1	21.2	13.8	35.4



Average Rainfall

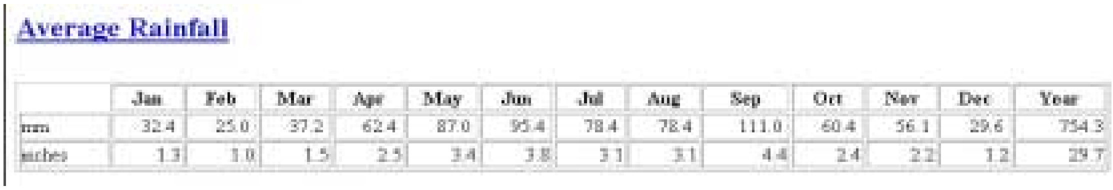
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	13.3	24.3	25.9	13.6	19.1	27.3	31.0	58.6	60.1	41.8	40.5	27.9	384.5
inches	0.5	1.0	1.0	0.5	0.8	1.1	1.2	2.3	2.4	1.6	1.6	1.1	15.1

MADISON



Average Temperature

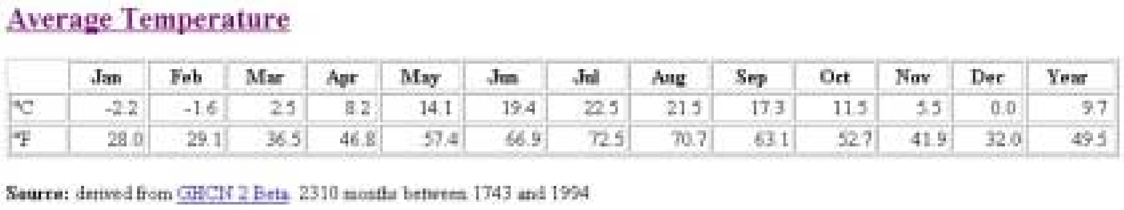
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	-8.0	-6.3	-0.2	7.6	14.2	19.5	22.3	21.0	16.4	10.0	1.8	-5.1	7.8
°F	17.6	20.7	31.6	45.7	57.6	67.1	72.1	69.8	61.5	50.0	35.2	22.8	46.0



Average Rainfall

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	32.4	25.0	37.2	62.4	87.0	95.4	78.4	78.4	111.0	60.4	56.1	29.6	754.3
inches	1.3	1.0	1.5	2.5	3.4	3.8	3.1	3.1	4.4	2.4	2.2	1.2	29.7

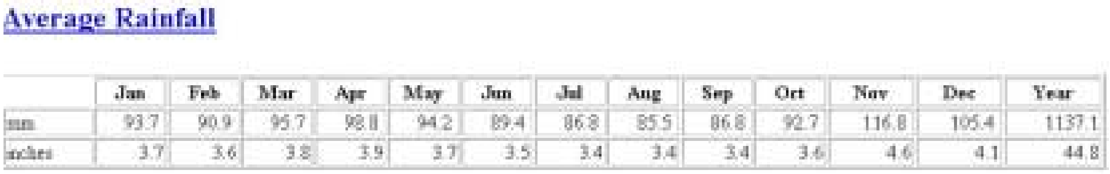
BOSTON



Average Temperature

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	-2.2	-1.6	2.5	8.2	14.1	19.4	22.5	21.5	17.3	11.5	5.5	0.0	9.7
°F	28.0	29.1	36.5	46.8	57.4	66.9	72.5	70.7	63.1	52.7	41.9	32.0	49.5

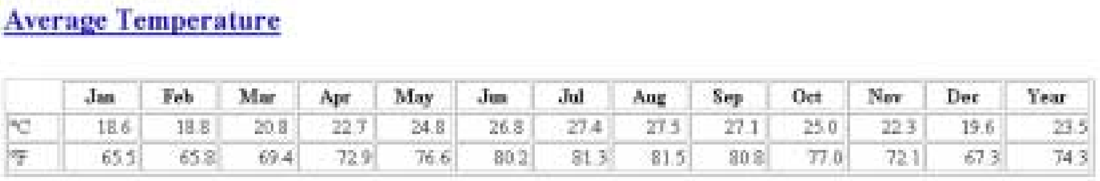
Source: derived from GHCN 2 Beta. 2310 months between 1743 and 1994



Average Rainfall

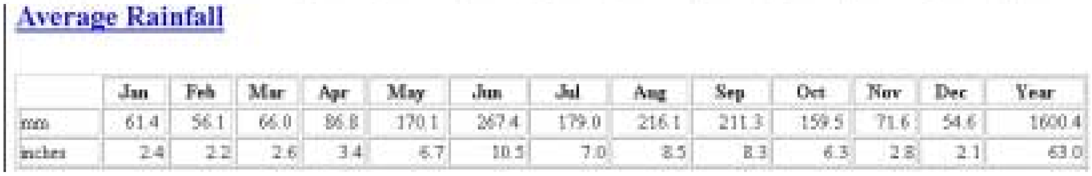
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	93.7	90.9	95.7	98.8	94.2	89.4	86.8	85.5	86.8	92.7	116.8	105.4	1137.1
inches	3.7	3.6	3.8	3.9	3.7	3.5	3.4	3.4	3.4	3.6	4.6	4.1	44.8

MIAMI



Average Temperature

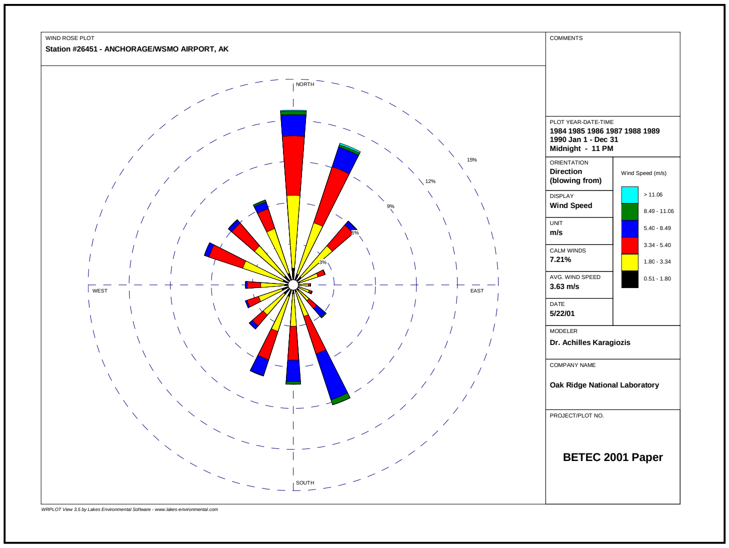
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
°C	18.6	18.8	20.8	22.7	24.8	26.8	27.4	27.5	27.1	25.0	22.3	19.6	23.5
°F	65.5	65.8	69.4	72.9	76.6	80.2	81.3	81.5	80.8	77.0	72.1	67.3	74.3



Average Rainfall

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mm	61.4	56.1	66.0	86.8	170.1	267.4	179.0	216.1	211.3	159.5	71.6	54.6	1600.4
inches	2.4	2.2	2.6	3.4	6.7	10.5	7.0	8.5	8.3	6.3	2.8	2.1	63.0

ANCHORAGE



WIND ROSE PLOT
Station #26451 - ANCHORAGE/WSMO AIRPORT, AK

COMMENTS

PLOT YEAR-DATE-TIME
1984 1985 1986 1987 1988 1989
1990 Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION
Direction
(blowing from)

DISPLAY
Wind Speed

UNIT
m/s

CALM WINDS
7.21%

AVG. WIND SPEED
3.63 m/s

DATE
5/22/01

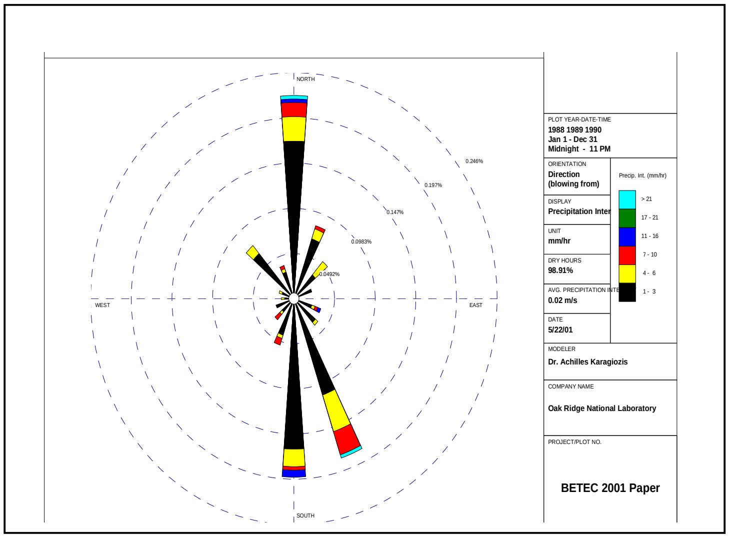
MODELER
Dr. Achilles Karagiozis

COMPANY NAME
Oak Ridge National Laboratory

PROJECT/PLOT NO.
BETEC 2001 Paper

WRPLOT View 3.5 by Lakes Environmental Software - www.lakes-environmental.com

Figure 2a: Wind Rose (Anchorage)



PLOT YEAR-DATE-TIME
1988 1989 1990
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION
Direction
(blowing from)

DISPLAY
Precipitation Inter

UNIT
mm/hr

DRY HOURS
98.91%

AVG. PRECIPITATION INTE
0.02 m/s

DATE
5/22/01

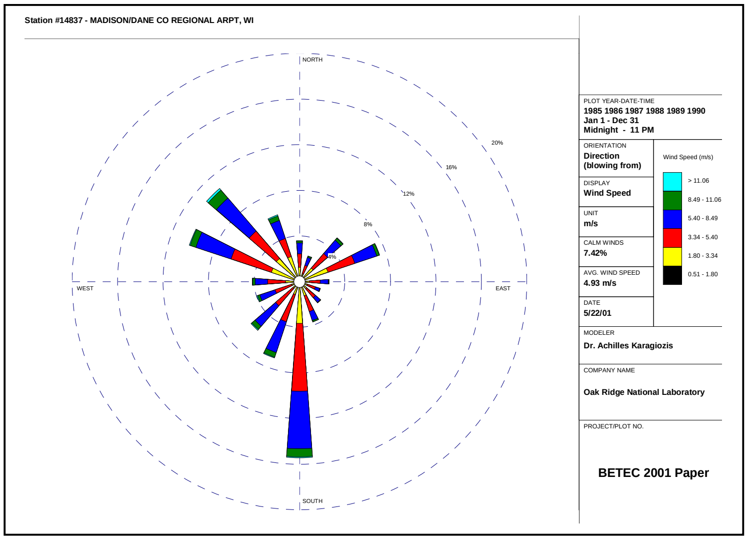
MODELER
Dr. Achilles Karagiozis

COMPANY NAME
Oak Ridge National Laboratory

PROJECT/PLOT NO.
BETEC 2001 Paper

Figure 2b: Rain Rose (Anchorage)

MADISON



Station #14837 - MADISON/DANE CO REGIONAL ARPT, WI

PLOT YEAR-DATE-TIME
1985 1986 1987 1988 1989 1990
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION
Direction
(blowing from)

DISPLAY
Wind Speed

UNIT
m/s

CALM WINDS
7.42%

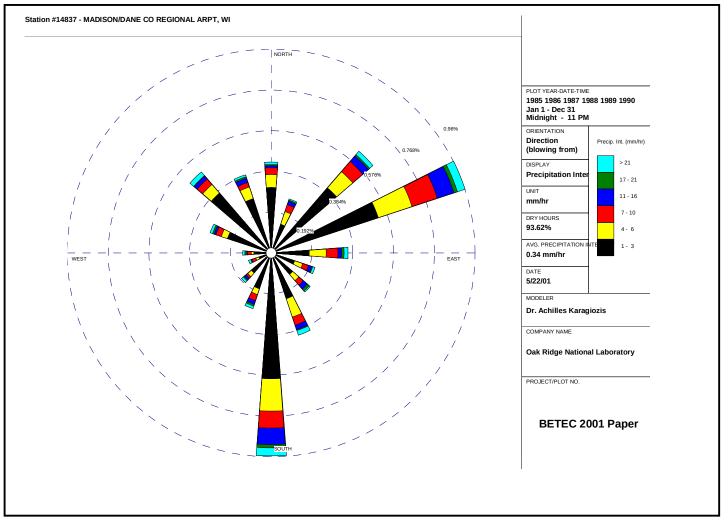
AVG. WIND SPEED
4.93 m/s

DATE
5/22/01

MODELER
Dr. Achilles Karagiozis

COMPANY NAME
Oak Ridge National Laboratory

PROJECT/PLOT NO.
BETEC 2001 Paper



Station #14837 - MADISON/DANE CO REGIONAL ARPT, WI

PLOT YEAR-DATE-TIME
1985 1986 1987 1988 1989 1990
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION
Direction
(blowing from)

DISPLAY
Precipitation Inter

UNIT
mm/hr

DRY HOURS
93.62%

AVG. PRECIPITATION INTE
0.34 mm/hr

DATE
5/22/01

MODELER
Dr. Achilles Karagiozis

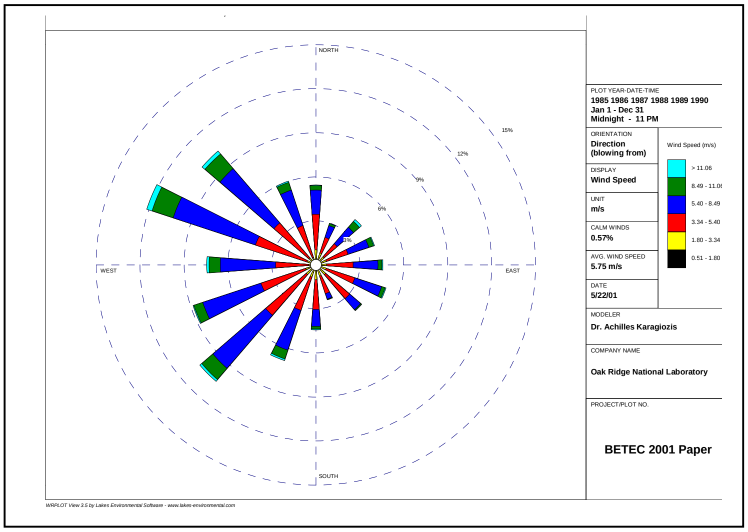
COMPANY NAME
Oak Ridge National Laboratory

PROJECT/PLOT NO.
BETEC 2001 Paper

Figure 2c: Wind Rose (Madison)

Figure 2d: Rain Rose (Madison)

BOSTON



PLOT YEAR-DATE-TIME
1985 1986 1987 1988 1989 1990
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION
Direction
(blowing from)

DISPLAY
Wind Speed

UNIT
m/s

CALM WINDS
0.57%

AVG. WIND SPEED
5.75 m/s

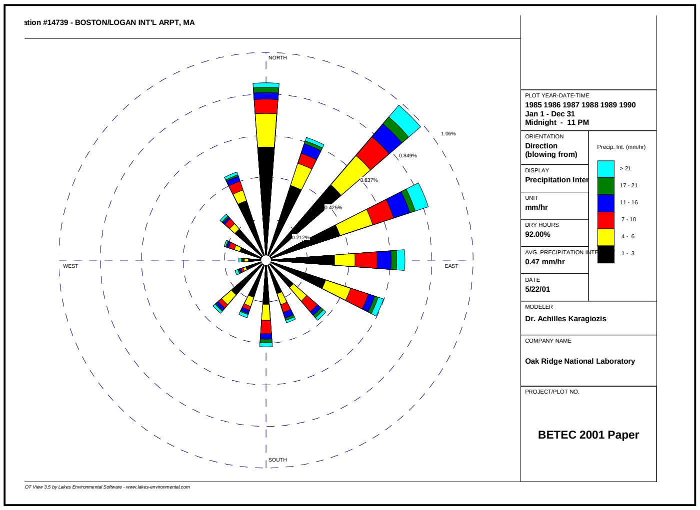
DATE
5/22/01

MODELER
Dr. Achilles Karagiozis

COMPANY NAME
Oak Ridge National Laboratory

PROJECT/PLOT NO.
BETEC 2001 Paper

Figure 2e: Wind Rose (Boston)



ation #14739 - BOSTON/LOGAN INT'L ARPT, MA

PLOT YEAR-DATE-TIME
1985 1986 1987 1988 1989 1990
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION
Direction
(blowing from)

DISPLAY
Precipitation Inter

UNIT
mm/hr

DRY HOURS
92.00%

AVG. PRECIPITATION INTE
0.47 mm/hr

DATE
5/22/01

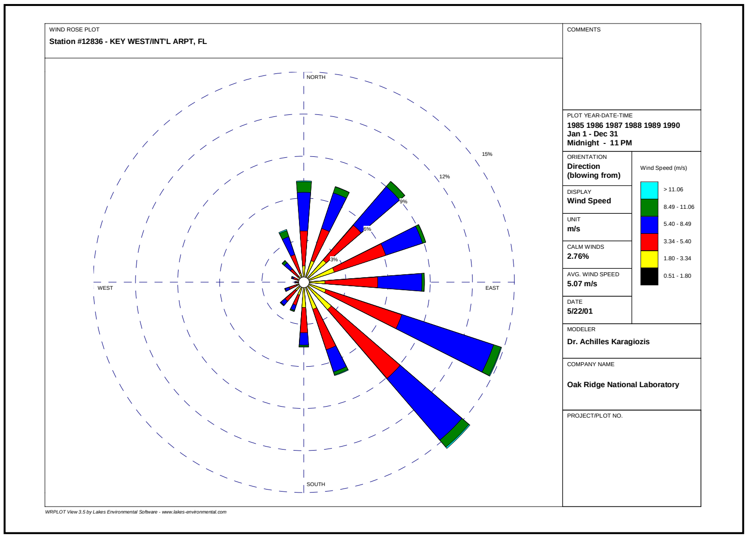
MODELER
Dr. Achilles Karagiozis

COMPANY NAME
Oak Ridge National Laboratory

PROJECT/PLOT NO.
BETEC 2001 Paper

Figure 2f: Rain Rose (Boston)

MIAMI



WIND ROSE PLOT
Station #12836 - KEY WEST/INT'L ARPT, FL

COMMENTS

PLOT YEAR-DATE-TIME
1985 1986 1987 1988 1989 1990
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION
Direction
(blowing from)

DISPLAY
Wind Speed

UNIT
m/s

CALM WINDS
2.76%

AVG. WIND SPEED
5.07 m/s

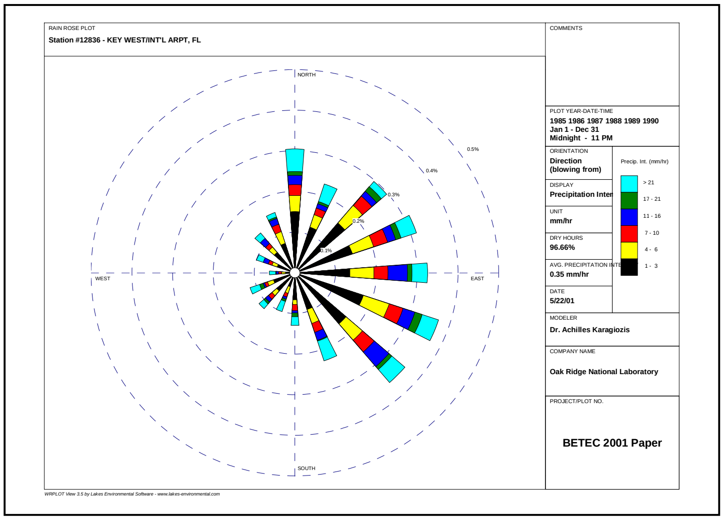
DATE
5/22/01

MODELER
Dr. Achilles Karagiozis

COMPANY NAME
Oak Ridge National Laboratory

PROJECT/PLOT NO.

Figure 2g: Wind Rose (Miami)



RAIN ROSE PLOT
Station #12836 - KEY WEST/INT'L ARPT, FL

COMMENTS

PLOT YEAR-DATE-TIME
1985 1986 1987 1988 1989 1990
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION
Direction
(blowing from)

DISPLAY
Precipitation Inter

UNIT
mm/hr

DRY HOURS
96.66%

AVG. PRECIPITATION INTE
0.35 mm/hr

DATE
5/22/01

MODELER
Dr. Achilles Karagiozis

COMPANY NAME
Oak Ridge National Laboratory

PROJECT/PLOT NO.
BETEC 2001 Paper

Figure 2h: Rain Rose (Miami)

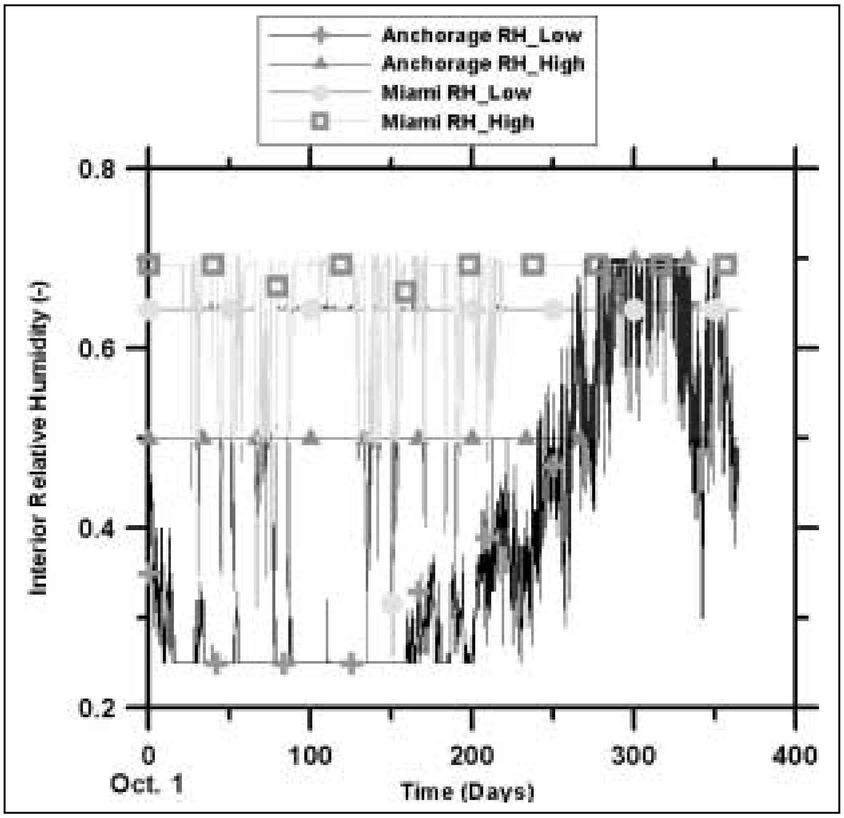


Figure 3: Interior Relative Humidity Conditions for Anchorage and Miami

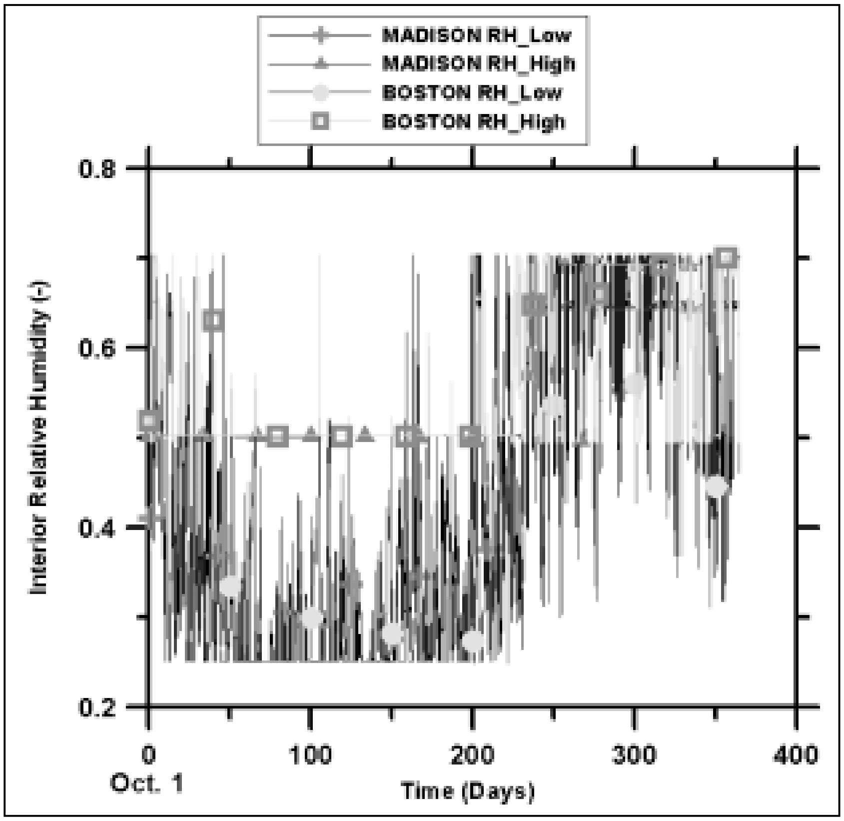


Figure 4: Interior Relative Humidity Conditions for Madison and Boston

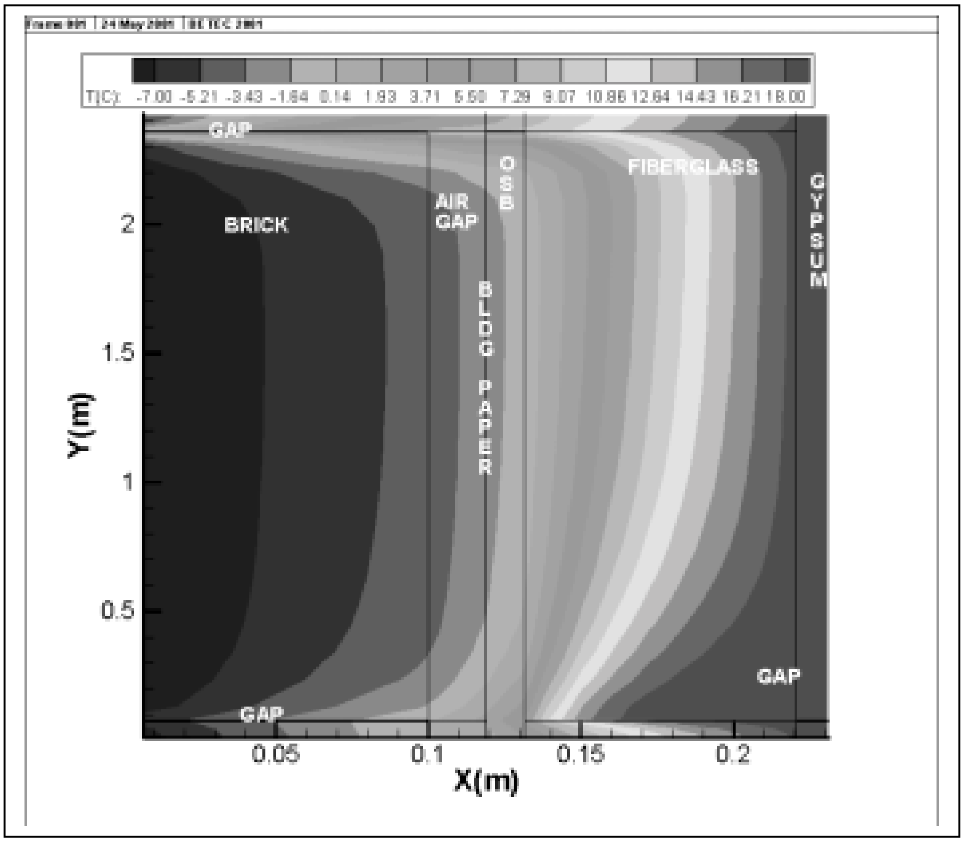


Figure 5: 2-D Temperature Conditions

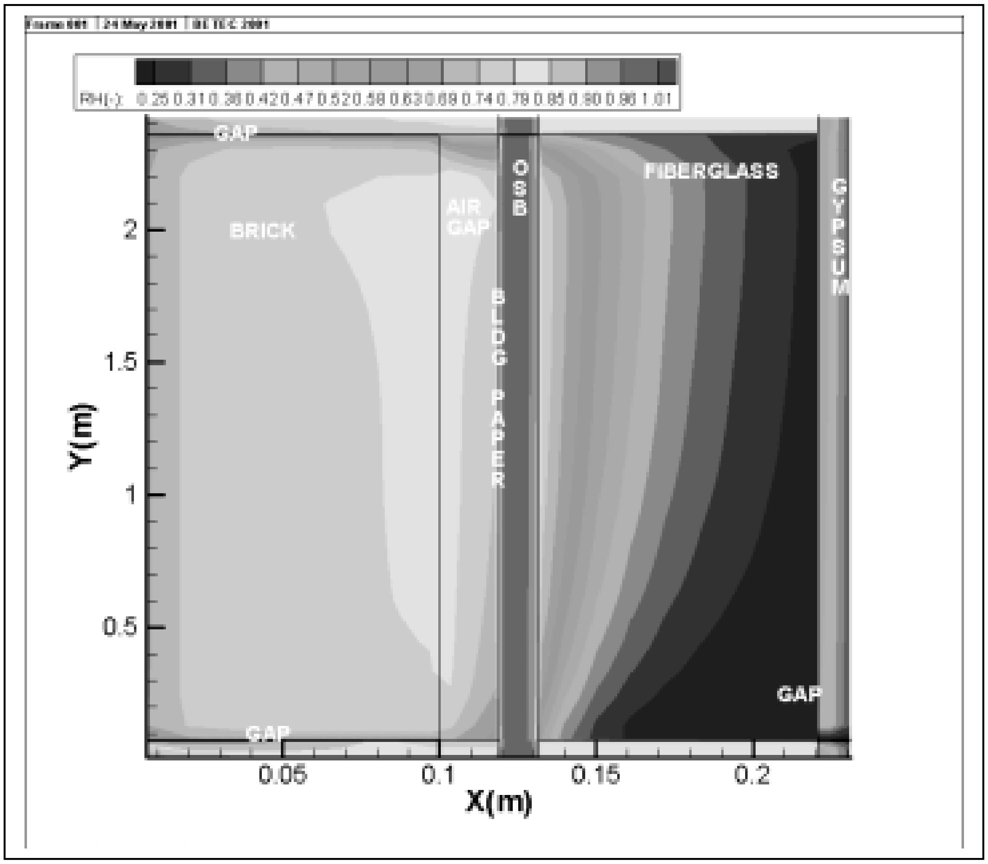


Figure 6: 2D Relative Humidity Conditions

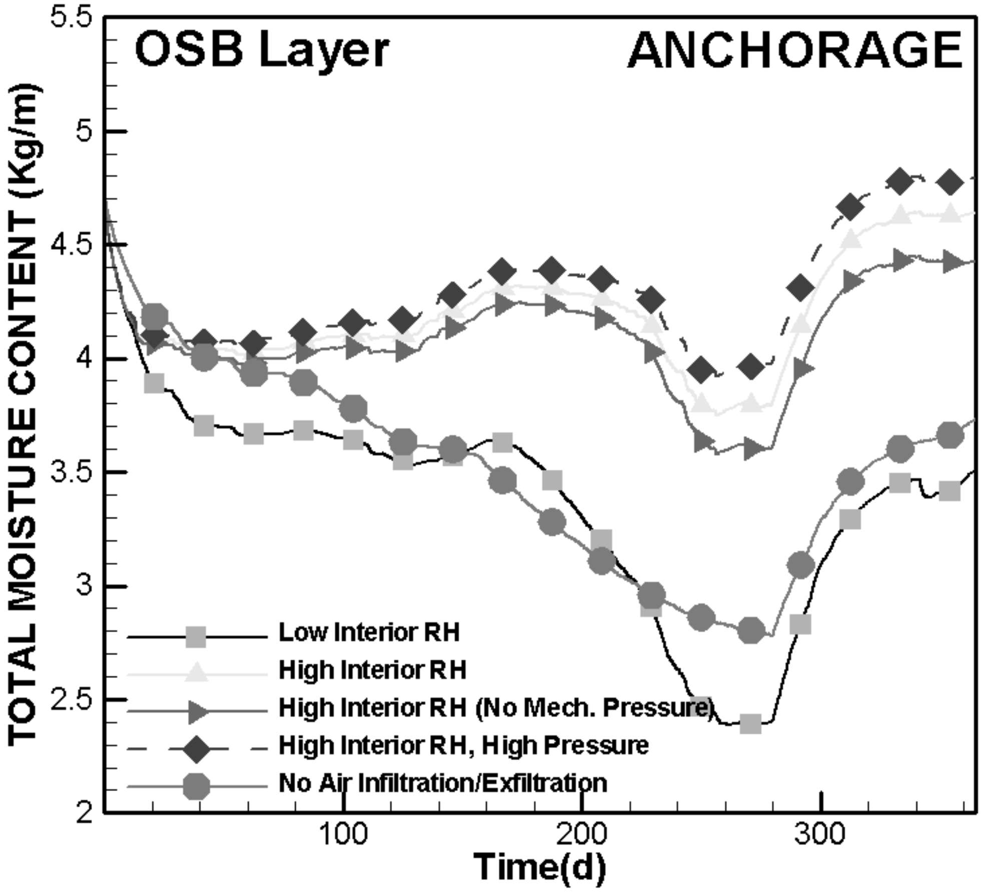


Figure 7: OSB Total Moisture Content (ANCHORAGE)

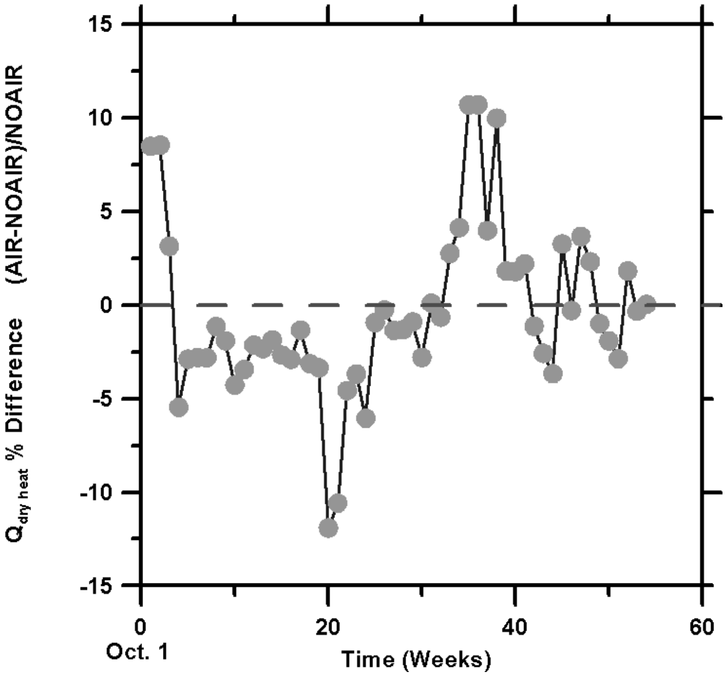


Figure 8: Air Leakage Difference in Weekly Heat Average Flux (ANCHORAGE)

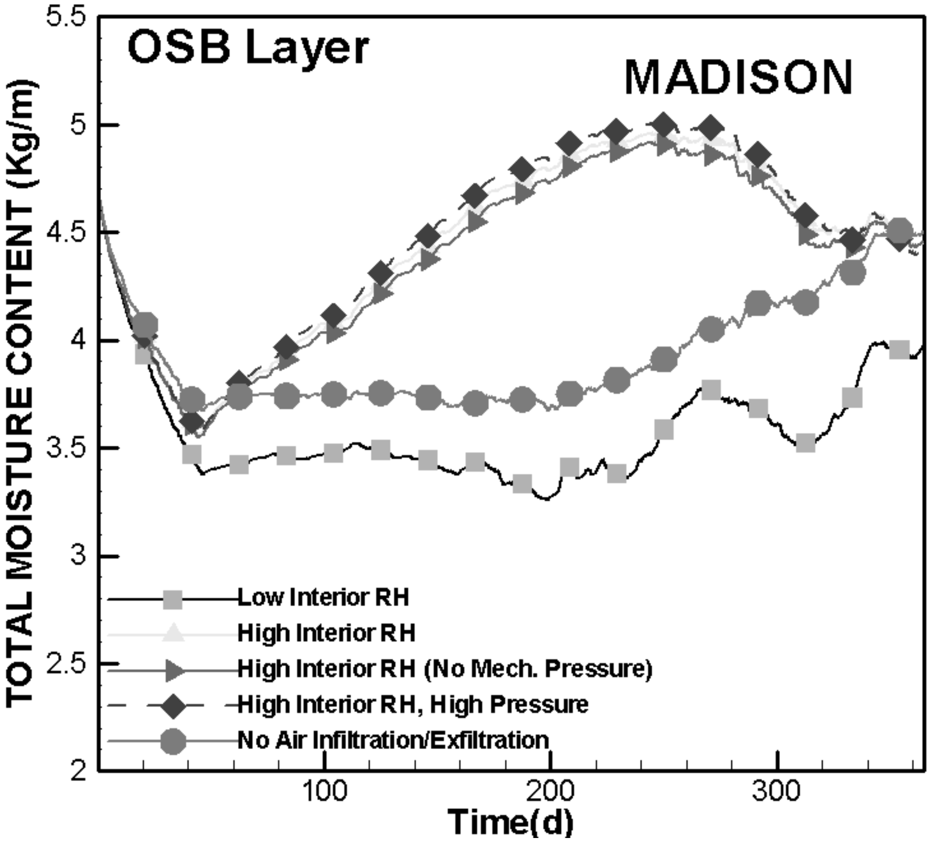


Figure 9: OSB Total Moisture Content (MADISON)

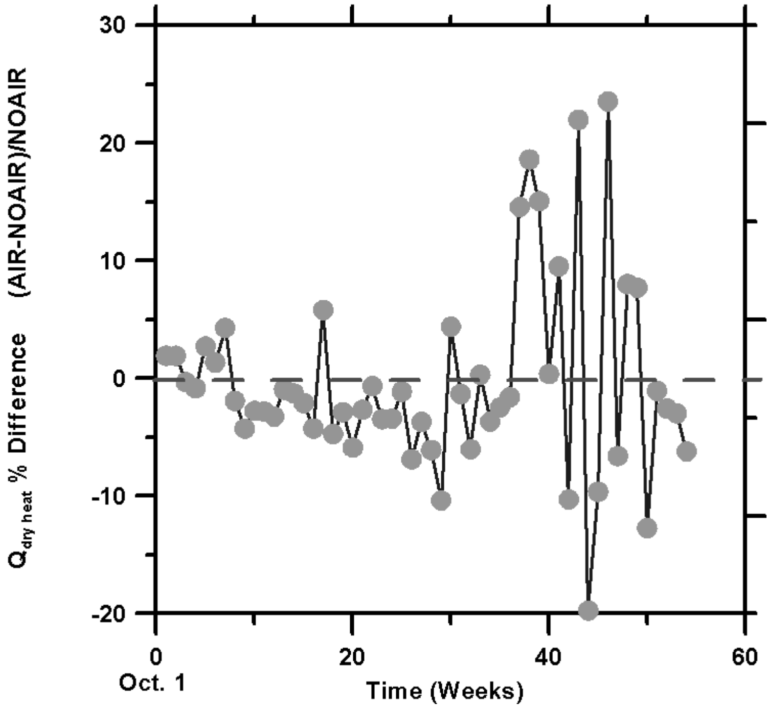


Figure10: Air Leakage Difference in Weekly Heat Average Flux (MADISON)

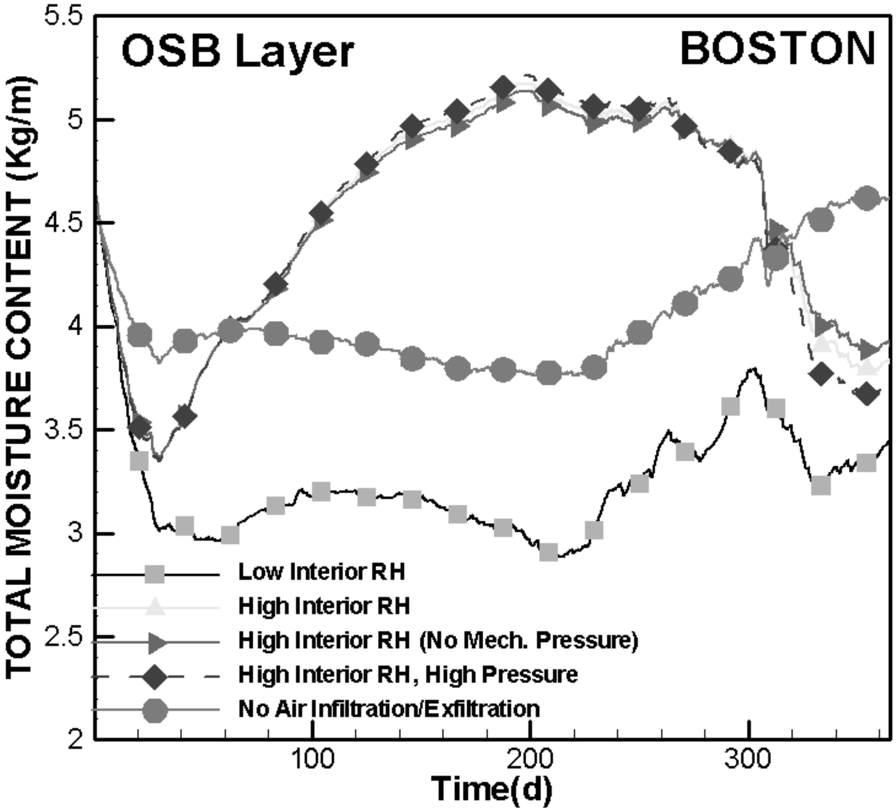


Figure 11: OSB Total Moisture Content (BOSTON)

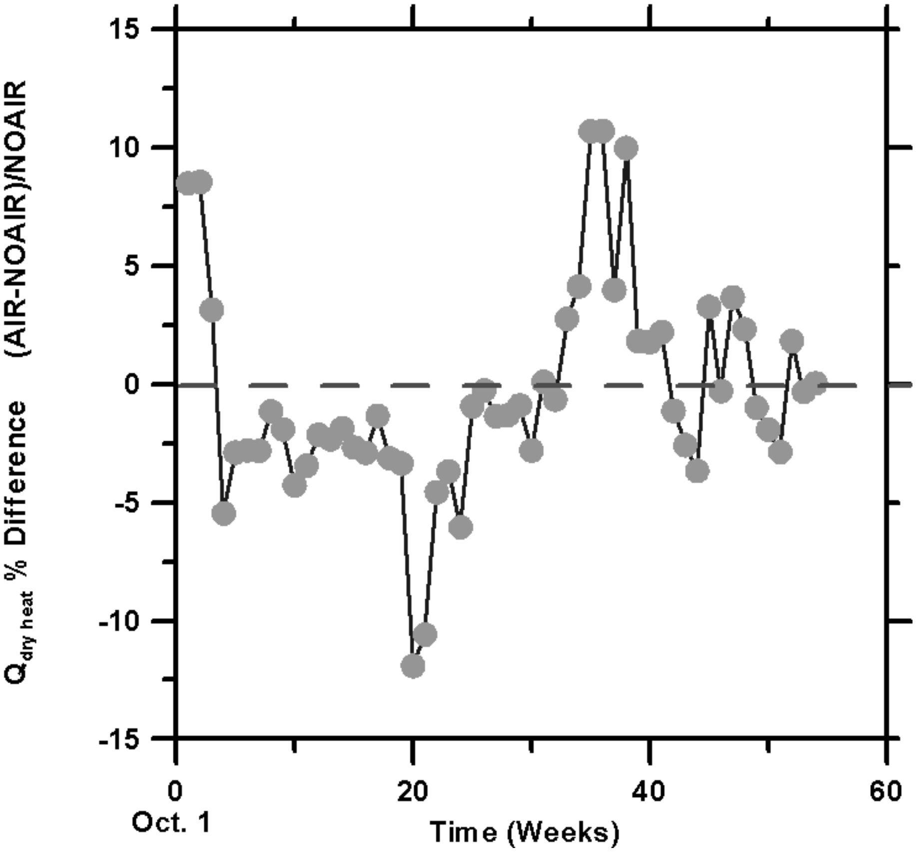


Figure 12: Air Leakage Difference in Weekly Heat Average Flux (BOSTON)

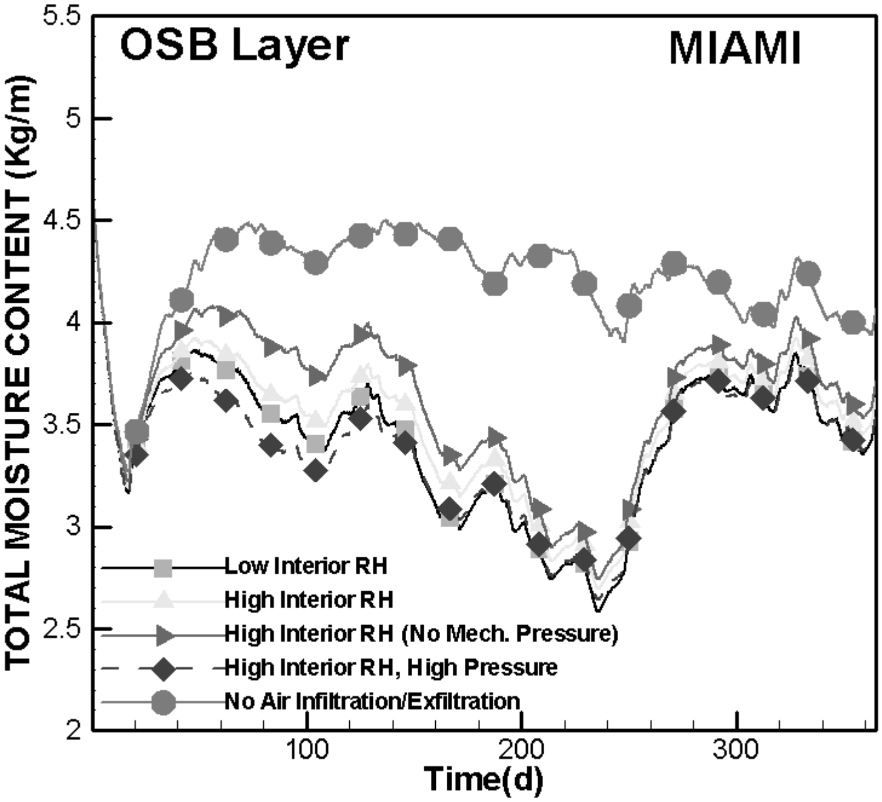


Figure 13: OSB Total Moisture Content (MIAMI)

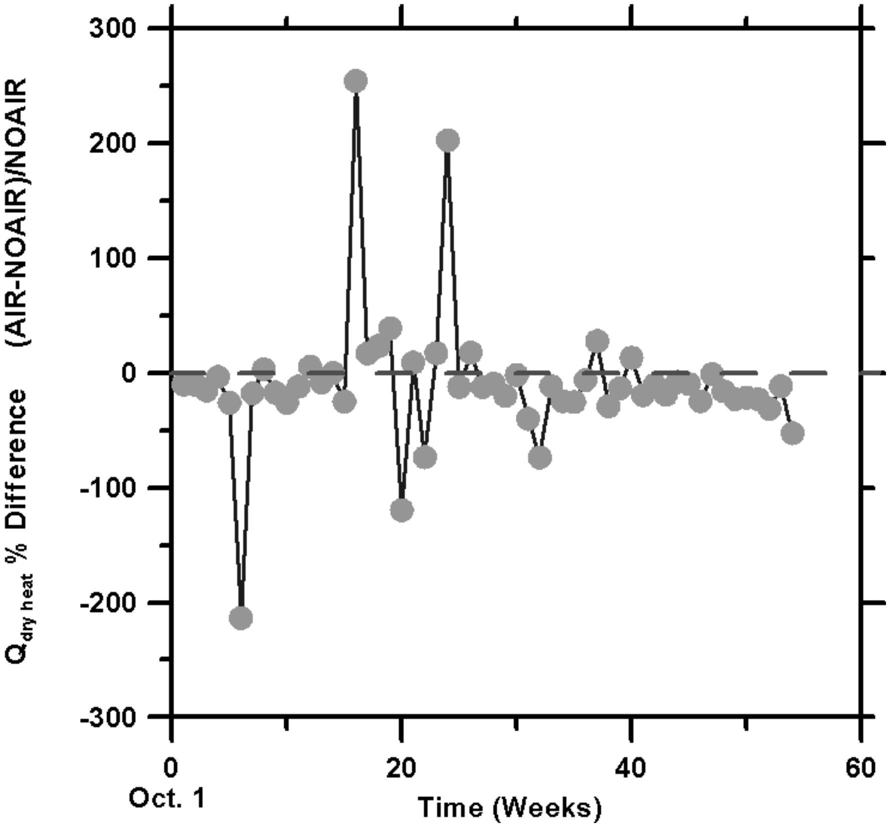


Figure 14: Air Leakage Difference in Weekly Heat Average Flux (MIAMI)