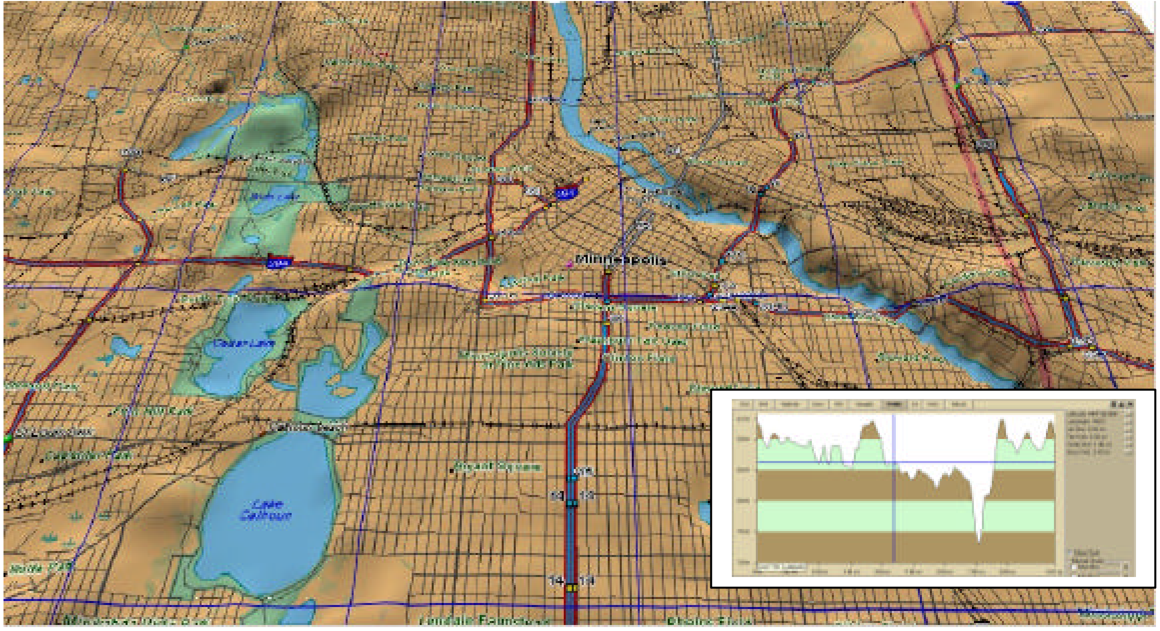
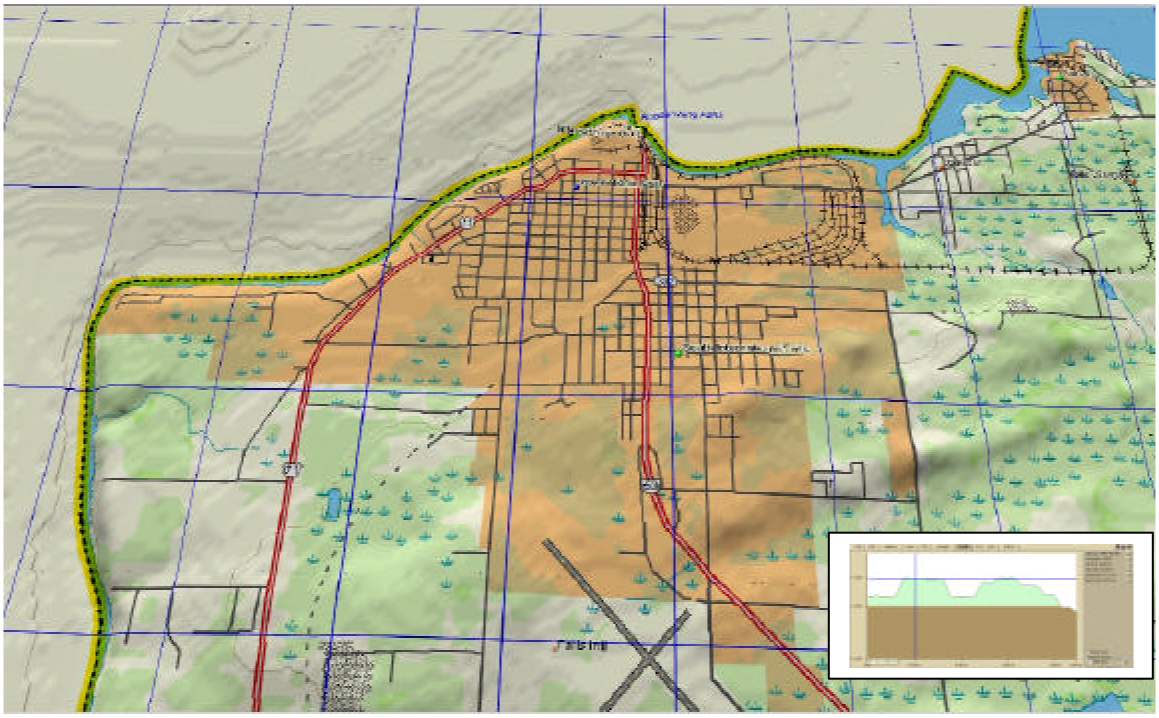
Activity 2: Load Analysis

Minneapolis, MN



International Falls, MN



Environmental Loads

Geographic Characteristics

Minnesota is located in the Northern Middle USA. In Figure 2.1, the average yearly rainfall is displayed in comparison to other locations in the US. Minnesota receives a US average amount of water each year. Precipitation includes both rainfall as well as snow. In Figure 2.2, the annual precipitation is displayed in terms of inches of water, and a distinct distribution of geographic precipitation isolines exist. The highest precipitation is observed near the Southeastern corner of the state, at values of more than 32 inches of water. The driest location is the Northwestern corner of the state, where annual precipitation values of less than 20 inches of water are found.

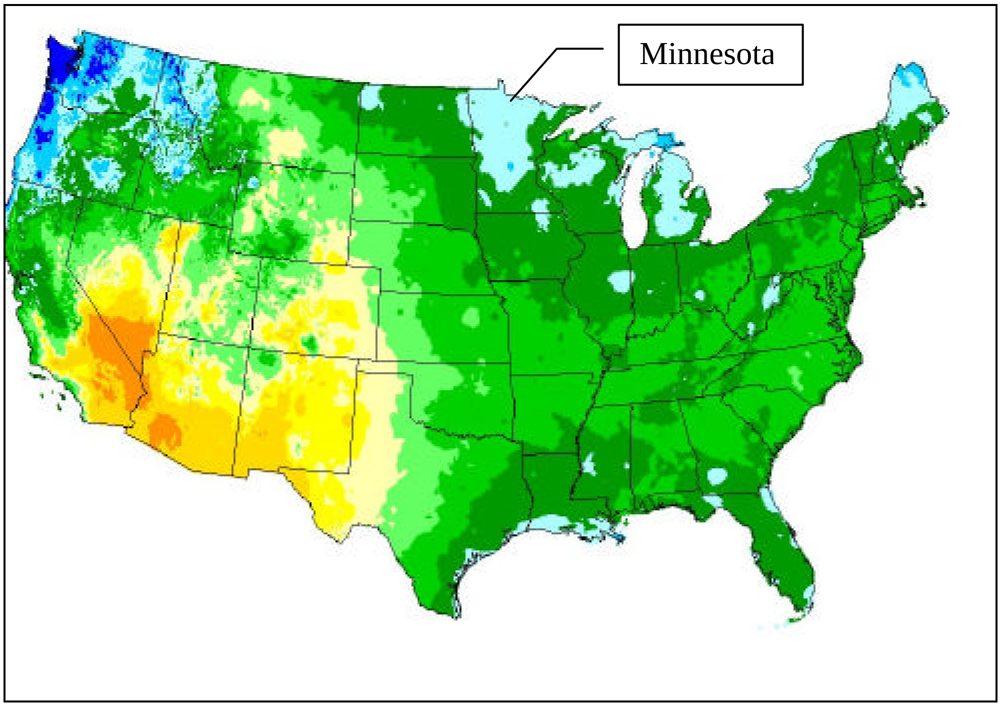


Figure 2.1: Geographic Location/Yearly Rainfall (Blue- High, Yellow-Low)

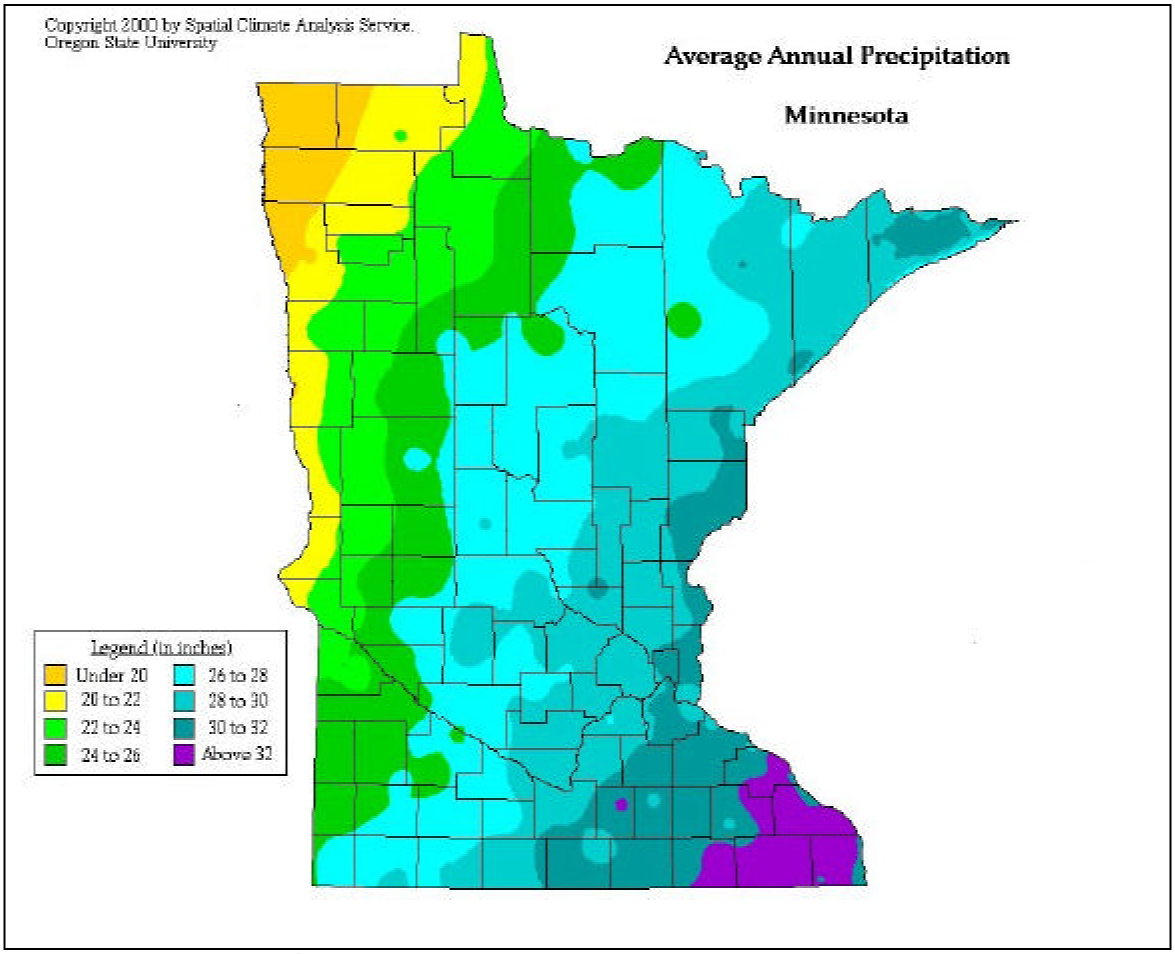


Figure 2.2: Average Annual Precipitation (Minnesota)

In Figure 2.3, the average yearly temperatures contours are displayed for the state of Minnesota derived from 30 years of hourly data from 1961 through 1990. Large average temperature differences of up to 14° F exist between the northern- and southernmost locations. Average yearly temperatures of 44 to 46° F are present at the southern regions of the Minnesota, while 32 to 34° F exist at the Northern and Northeastern regions.

The US National Climatic Data Center (NCDC) provides 4 locations with 30-year weather data (SAMSON) that include solar radiation and rainfall precipitation data for the state of Minnesota. These four meteorological locations are: Minneapolis, St. Cloud, International Falls, and Rochester. As described in Table 1 of the proposal, due to the apparent time constraints, two locations were selected. Two of these have been selected to represent conditions that contain the widest characteristics of possible conditions present in (populated) Minnesota. The two selected were:

a) Minneapolis, MN
b) International Falls MN

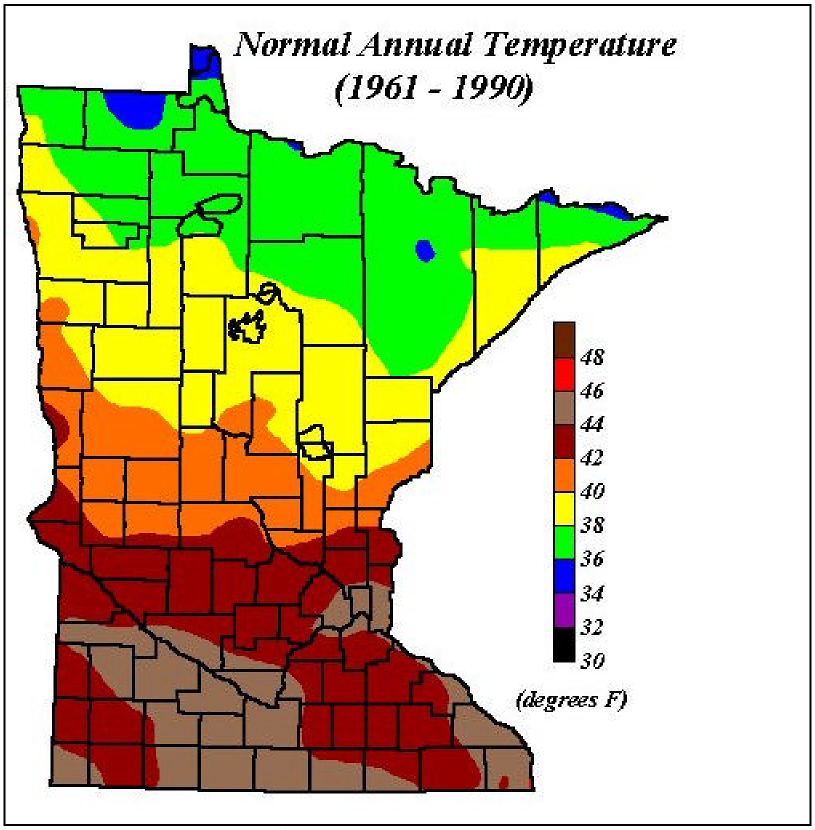


Figure 2.3: Average Yearly Temperature in Minnesota

Figures 4 and 5 displays 30 year plots of the monthly average, minimum and extreme temperatures, monthly rain precipitation, monthly cooling degree days (based on 65° F) and heating degree days for the two selected cities. The results show the differences between these two cities in terms of the ambient conditions, pointing out the much colder conditions at International Falls. These locations will be used in the extensive hygrothermal modeling activity, that is, Activity 3: *Advanced Moisture Engineering/Modeling.*

The first activity required was to develop Moisture Design Years from the 30 year hourly data, by selecting years that represent hygric loads appropriate for moisture design purposes. In the past, hygrothermal modeling used weather data from energy calculation models. Weather years for energy calculations have serious limitations when employed in hygrothermal modeling, as the criteria for their selection is completely different. An analysis procedure developed at the International Energy Agency (IEA), *Annex 24 on Heat, Air and Moisture Transport in Highly Insulated Building Envelopes,* is used in this project to develop two weather years that coincide with the 10 % percentile coldest and warmest years with corresponding hygric loads, which are significantly different from those used in energy calculations. The influence of rain loads is included in the analysis determining the hygric loads. The reason for using the 10% percentile (rather than the worst conditions) is that a seasonal adjusted condensation load may be allowed to occur once every 10 years. This load is expected be effectively dissipated by the envelope systems, as some moisture capacity in terms of storage and release is present in most walls.

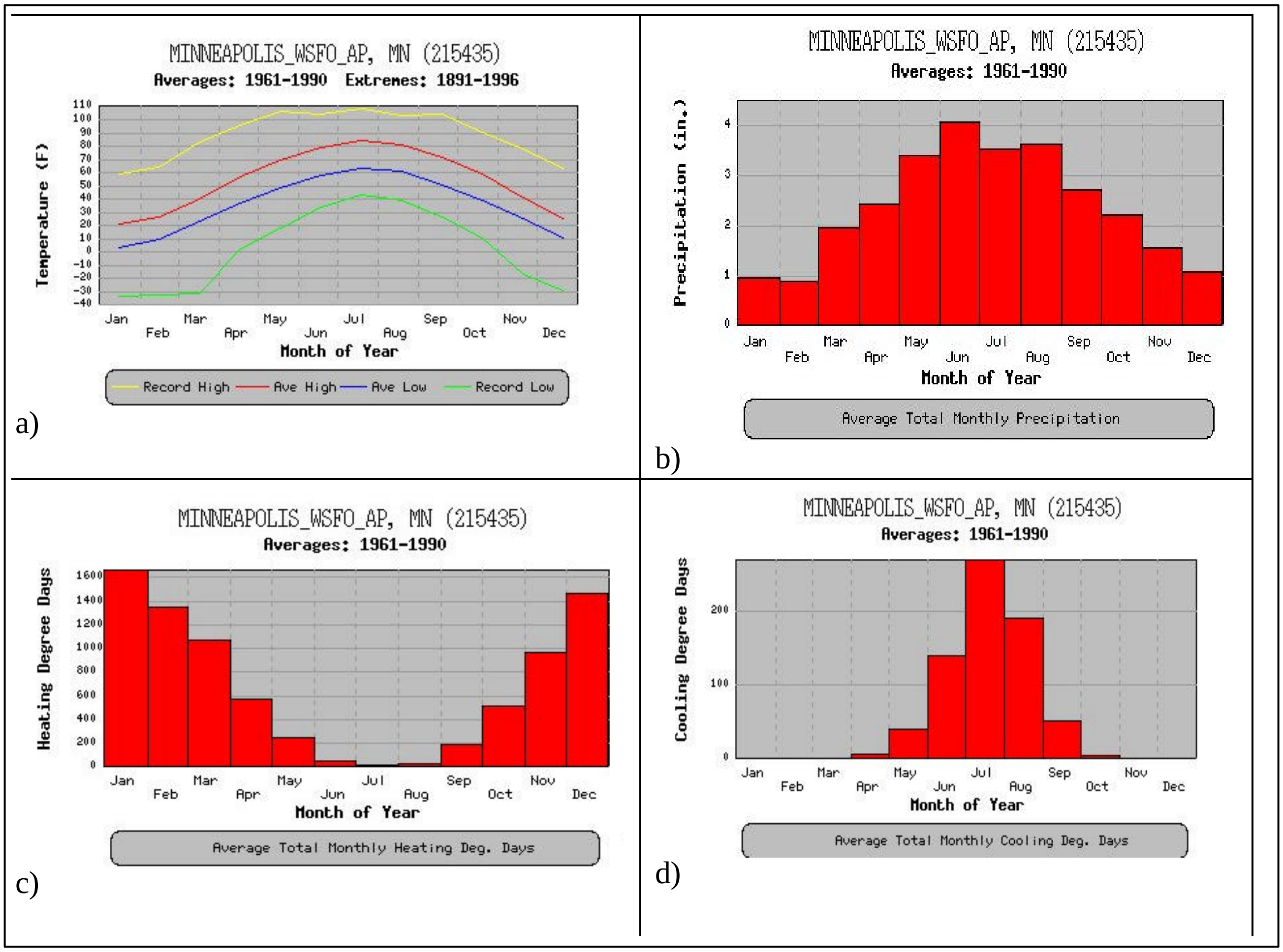


Figure 2.4: Minneapolis Climatic Conditions

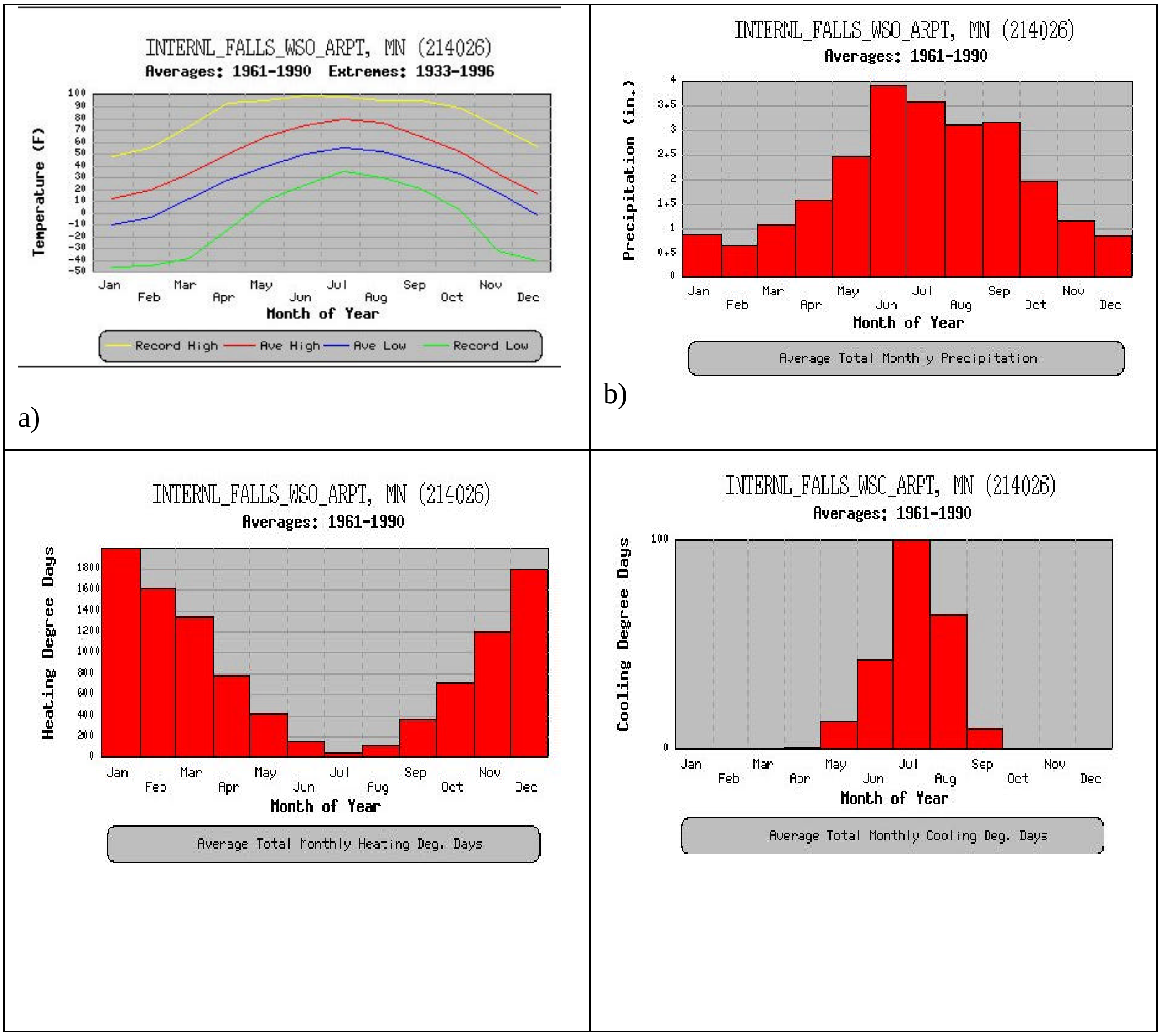


Figure 2.5: International Falls Climatic Conditions

In Figure 2.6, the monthly average vapor pressure distribution is plotted for the city of Minneapolis. Thirty years of hourly data were processed spanning through the period between 1961-1990. During the year, the vapor pressure of the exterior is consistently lower than 900 Pa for approximately 6 months of the year. This indicates a healthy drying potential towards the outside of the structure for vapor diffusion transport.

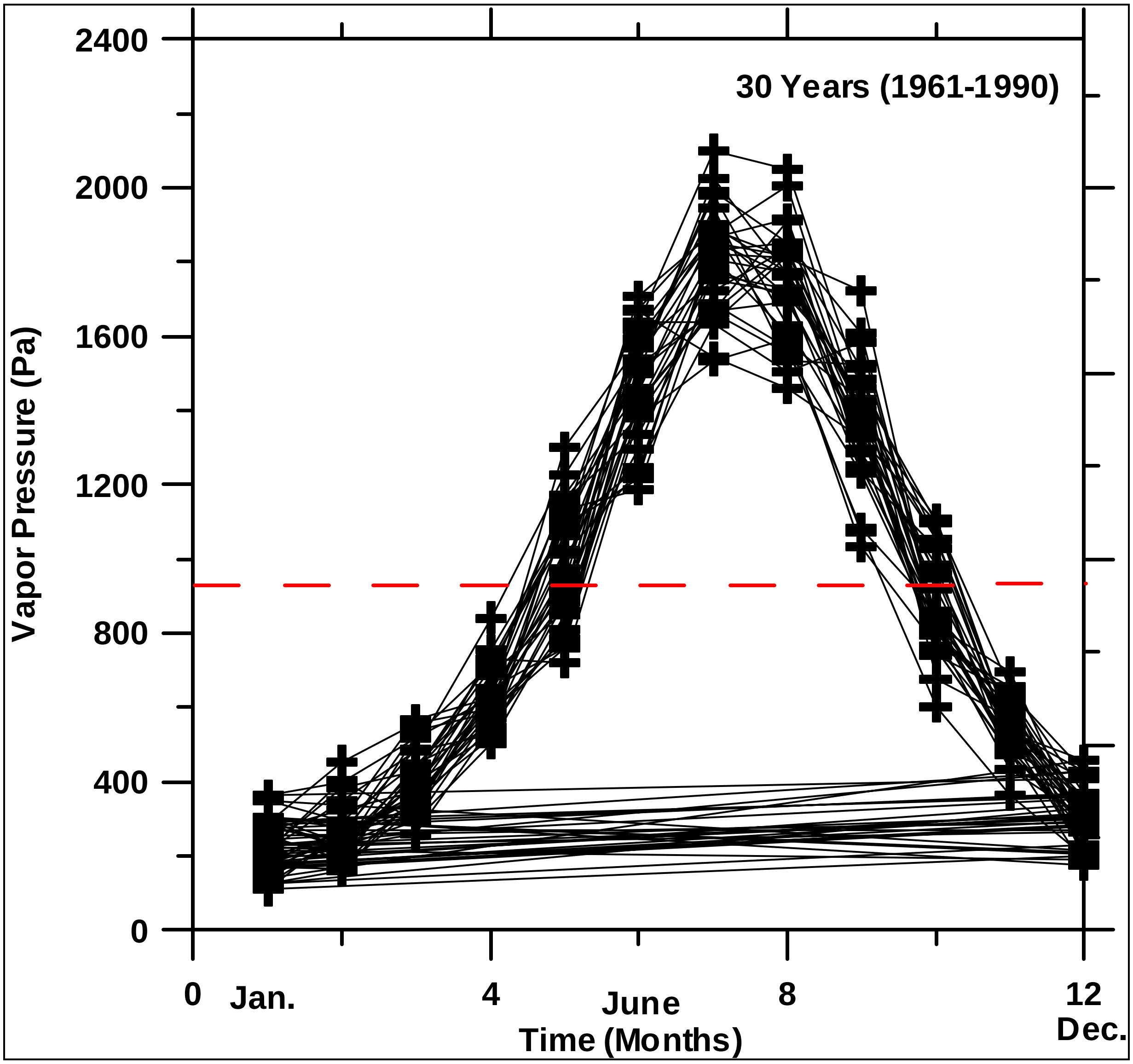


Figure 2.6: Vapor Pressure Distribution for Minneapolis

In Figure 2.7, the monthly average vapor pressure distribution is plotted for the city of International falls. The results show even drier conditions are present in terms of vapor moisture than for the city of Minneapolis. A maximum of 8 months per year of possible drying conditions are available for International Falls.

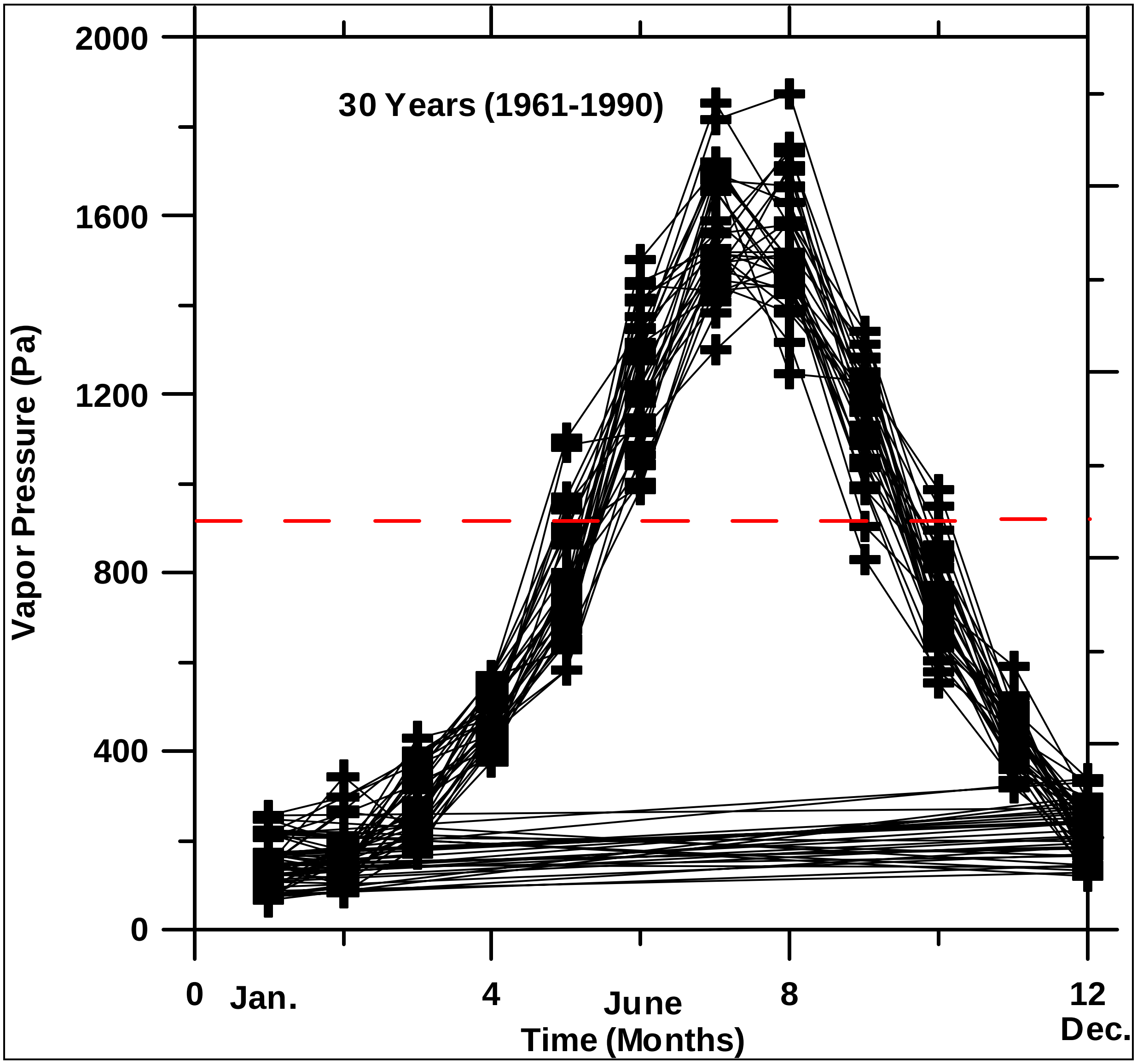


Figure 2.7: Vapor Pressure Distribution for International Falls

In Tables 1 and 2, yearly averaged hygrothermal loads are given for both locations.

Table 1: Synopsis of Hygric Loads for Minneapolis

Year	#	Temp	PV	RH	Rain
1961	1	7.0877	921.131	71.5778	661.199
1962	2	6.1871	912.707	72.4339	744.498
1963	3	7.1550	949.256	69.3322	505.099
1964	4	7.7221	913.351	68.7941	667.099
1965	5	6.2446	856.628	72.2614	1,023.997
1966	6	6.5737	864.861	67.3847	625.699
1967	7	6.2631	825.349	68.2100	654.399
1968	8	7.6428	924.982	68.2347	972.098
1969	9	7.2501	891.647	69.0155	508.698
1970	10	7.0601	927.484	68.4938	785.997
1971	11	7.0936	844.420	65.3789	755.998
1972	12	5.4736	856.530	68.6249	589.499
1973	13	8.5220	919.322	67.6013	573.299
1974	14	7.0904	837.395	66.8468	493.099
1975	15	7.4319	905.406	68.0818	902.498
1976	16	8.3433	777.613	56.6604	425.199
1977	17	7.3800	937.291	67.6958	888.698
1978	18	7.0807	917.765	65.9986	783.698
1979	19	6.5391	849.579	64.8740	801.898
1980	20	7.5691	823.199	61.9145	561.299
1981	21	8.3126	886.026	65.6860	714.398
1982	22	7.1293	873.390	66.2100	743.698
1983	23	7.9101	1,013.136	74.2937	1,042.490
1984	24	7.4294	870.221	65.5193	941.198
1985	25	6.7013	848.034	65.9071	822.298
1986	26	7.6622	961.181	73.6554	941.698
1987	27	10.0873	970.919	67.0744	821.099
1988	28	8.3551	869.660	63.1444	481.599
1989	29	6.7414	869.720	66.6654	609.699
1990	30	8.8172	936.489	66.5858	851.898

Table 2: Synopsis of Hygric Loads for International Falls

Year	#	Temp	PV	RH	Rain
1961	1	3.7599	724.496	70.2469	637.998
1962	2	2.7933	741.262	72.2317	738.298
1963	3	3.5015	798.230	70.8043	642.298
1964	4	3.1251	766.211	74.6551	688.698
1965	5	2.0930	707.738	74.0758	752.797
1966	6	1.8551	741.621	71.4991	666.099
1967	7	2.0395	667.887	67.8225	569.198
1968	8	3.0470	746.258	73.0062	748.997
1969	9	2.7949	725.321	73.1604	610.298
1970	10	2.5831	731.730	71.1393	586.398
1971	11	2.7945	751.017	72.9175	639.498
1972	12	2.2206	672.585	64.8801	483.599
1973	13	4.6916	744.139	65.8969	747.198
1974	14	2.7070	627.617	61.8729	626.498
1975	15	2.9880	737.973	68.8606	664.499
1976	16	2.6871	700.352	68.7152	563.699
1977	17	3.1164	769.288	72.0554	823.697
1978	18	1.8889	690.735	65.2392	640.398
1979	19	1.0676	678.682	71.4441	578.399
1980	20	3.4433	699.539	66.8147	511.698
1981	21	4.9899	794.688	72.1360	567.498
1982	22	2.2655	780.058	75.5243	642.398
1983	23	4.0016	825.154	75.0632	648.797
1984	24	3.2960	745.223	70.9339	542.698
1985	25	1.7007	691.675	73.2261	788.597
1986	26	3.8001	750.841	73.4946	469.998
1987	27	5.9888	788.955	70.8743	505.699
1988	28	3.7327	759.751	70.7918	635.798
1989	29	2.3553	733.293	71.2032	590.199
1990	30	4.2575	741.166	69.8790	526.299

Wind-driven rain is a critical hygrothermal load. Indeed, in most instances, this load is several times greater than all other load combined. As such, the selection of orientation for the hygrothermal simulations must be assigned based on analysis of the amount of water load each orientation receives. The maximum load must be established for each orientation before a moisture engineering analysis is preformed. This requires a better understanding of the prominent wind direction and concurrent wind driven rain occurrences. In this project, this analysis was performed for both weather files (10% percentile cold and hot year) used in the hygrothermal simulations.

In Figures 8 and 9, the rain and wind roses are plotted out using the selected moisture design years for Minneapolis. In Minneapolis, 3.78% of the time, calm winds exist (lower than 0.5 m/s or 1 mph), while the average wind speed is 4.83 m/s (11 mph). Prominent wind directions are northwest and southeast, but south and southwest directions also show wind movement. From the rain rose plots, wind-driven rain activity exists in three main quadrants, spanning from northwest to southeast.

In Figures 10 and 11, wind and rain roses are plotted out for International Falls. For this location, calm winds exist 8.23% of the time, more than twice as long as in Minnesota. The average wind speed is 4.32 m/s (10 mph), slightly lower than for Minneapolis. The average precipitation for Minneapolis is 0.19 mm/hr (0.0075 in/hr) while for International Falls a value of 0.32 mm/hr (0.0126 in/hr) exists.

All results presented in the rain roses include the effect of precipitation in both liquid and ice phase (snow).

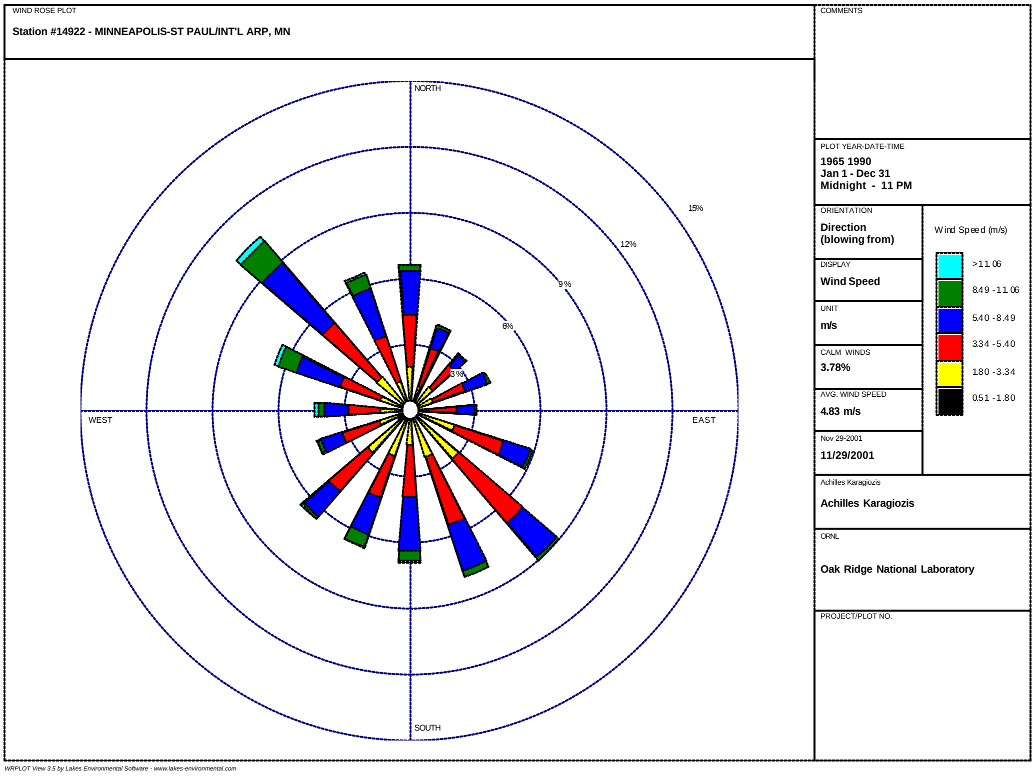


Figure 2.8: Wind Speed Rose for Minneapolis

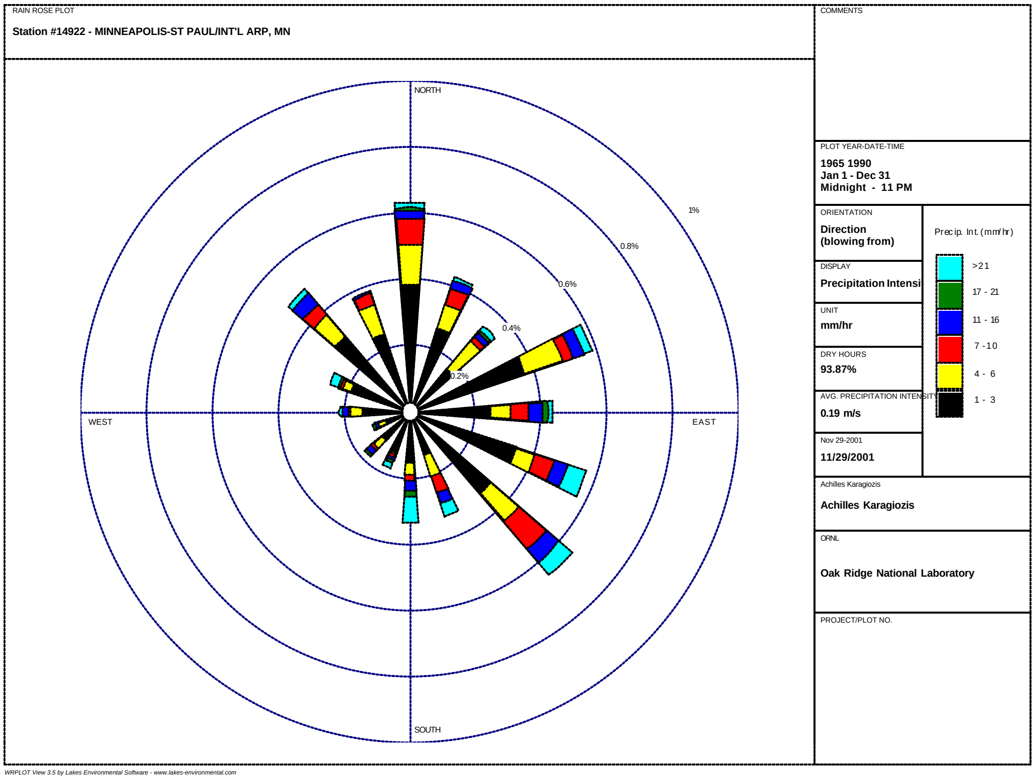
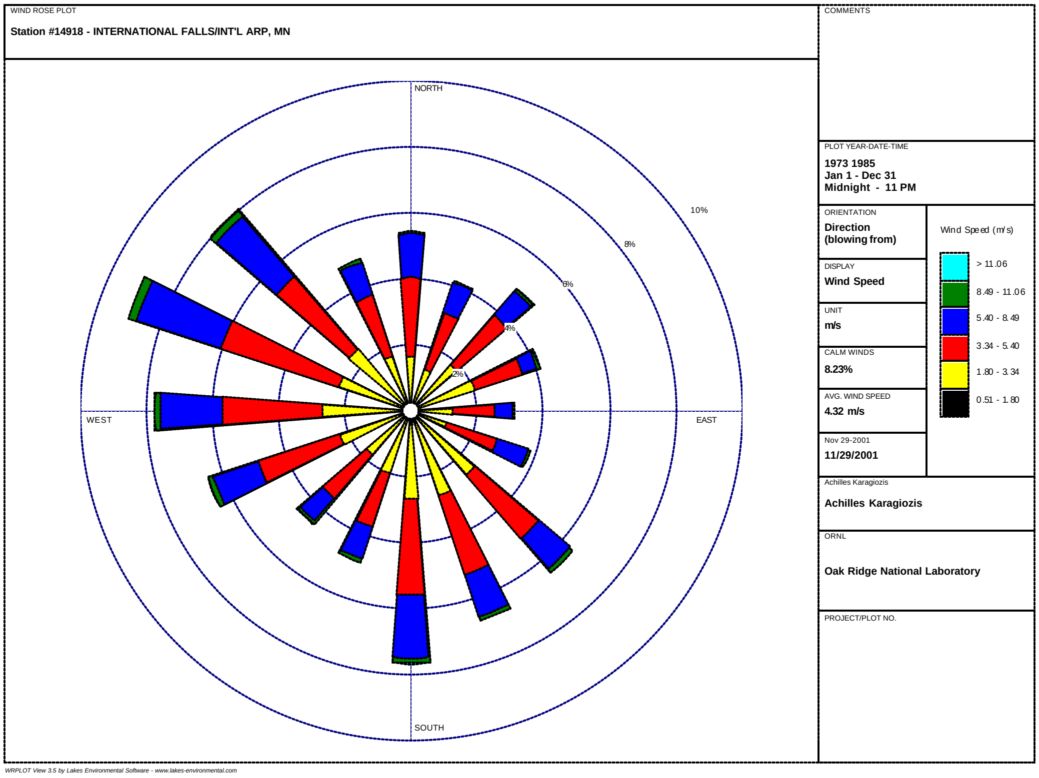


Figure 2.9: Rain Rose for Minneapolis



WIND ROSE PLOT

Station #14918 - INTERNATIONAL FALLS/INT'L ARP, MN

COMMENTS

PLOT YEAR-DATE-TIME

1973 1985
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION

Direction
(blowing from)

DISPLAY

Wind Speed

UNIT

m/s

CALM WINDS

8.23%

AVG. WIND SPEED

4.32 m/s

Nov 29-2001

11/29/2001

Achilles Karagiozis

Achilles Karagiozis

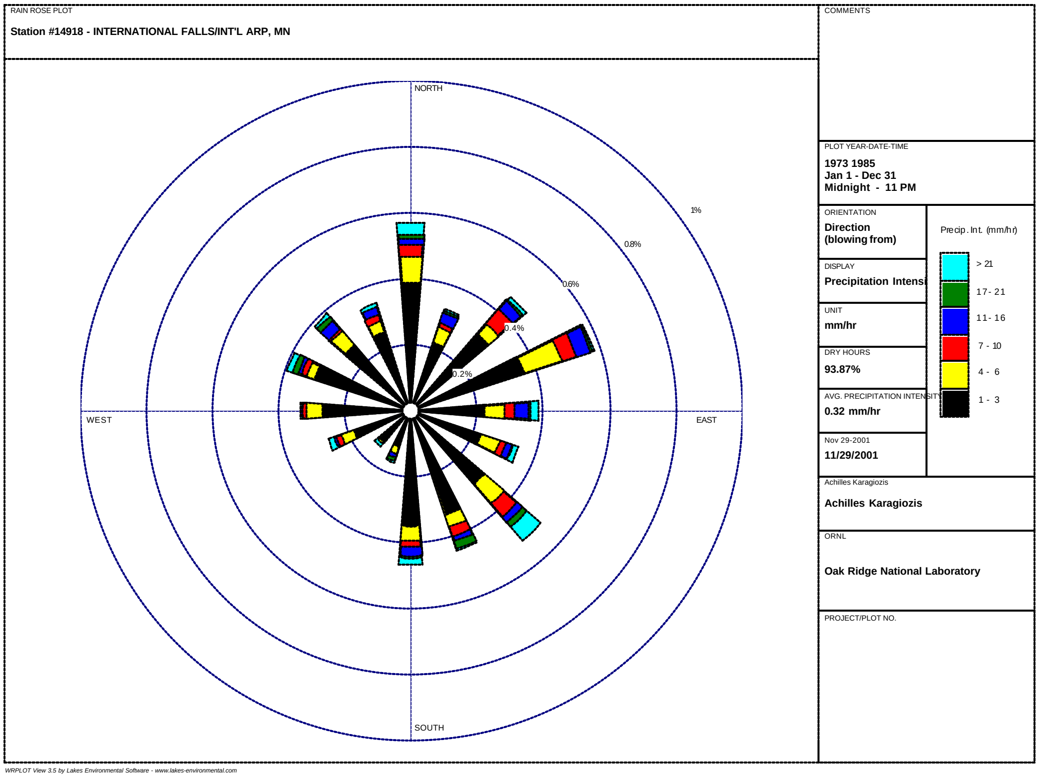
ORNL

Oak Ridge National Laboratory

PROJECT/PLOT NO.

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

Figure 2.10: Wind Speed Rose for International Falls



RAIN ROSE PLOT

Station #14918 - INTERNATIONAL FALLS/INT'L ARP, MN

COMMENTS

PLOT YEAR-DATE-TIME

1973 1985
Jan 1 - Dec 31
Midnight - 11 PM

ORIENTATION

Direction
(blowing from)

DISPLAY

Precipitation Intensi

UNIT

mm/hr

DRY HOURS

93.87%

AVG. PRECIPITATION INTENSITY

0.32 mm/hr

Nov 29-2001

11/29/2001

Achilles Karagiozis

Achilles Karagiozis

ORNL

Oak Ridge National Laboratory

PROJECT/PLOT NO.

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

Figure 2.11: Rain Rose for International Falls

In Figures 2.12a through 2.13b, the wind-driven rain on four orientations is plotted out. In Figures 2.12a and 2.13a, the maximum rainfall possible over a 180° angle is plotted out. In 2.12b and 2.13b, the actual amount impinging is displayed.

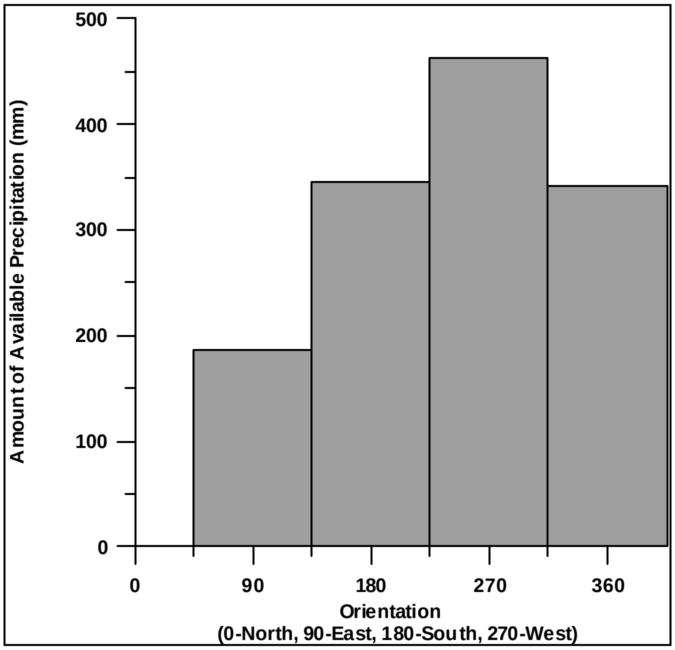


Figure 2.12a: Possible Rain (before effect of Wind) for Minneapolis

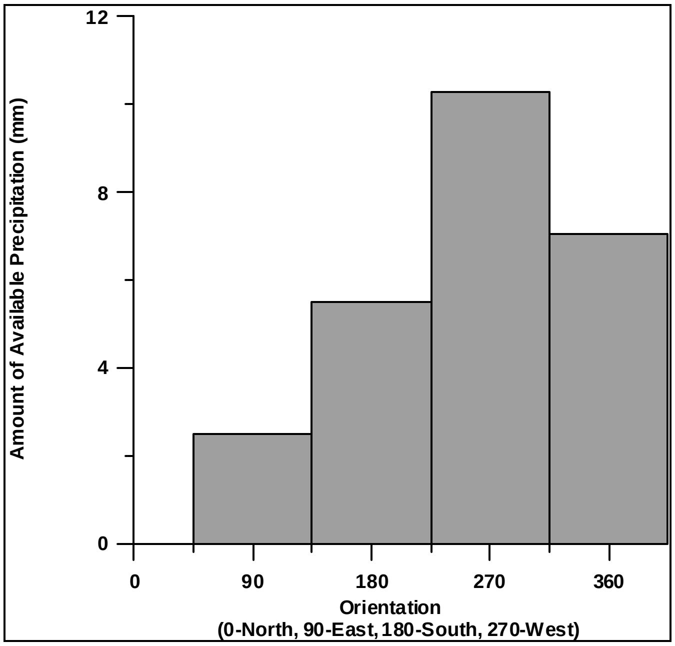


Figure 2.12b: WDR (Wind-driven rain) for Minneapolis

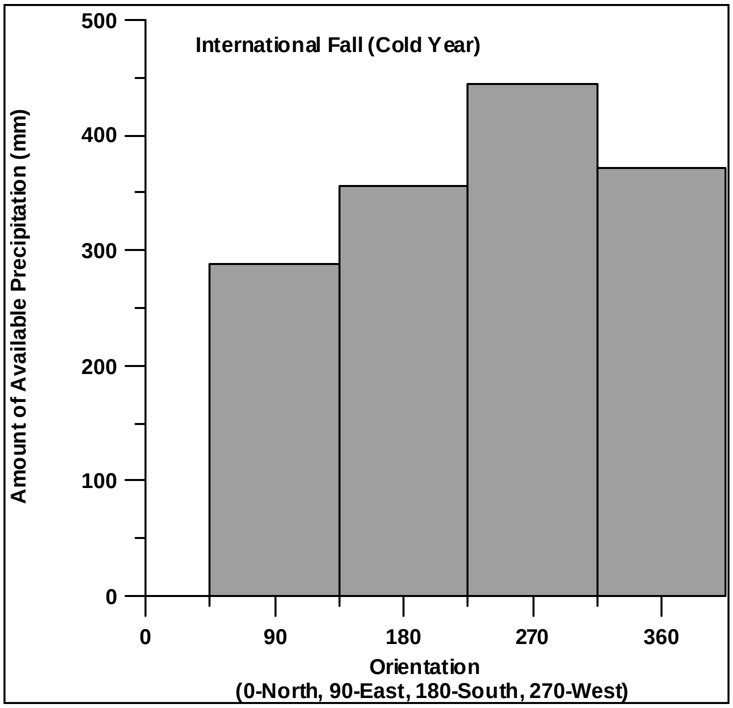


Figure 2.13a: Possible Rain (before effect of Wind) for International Falls

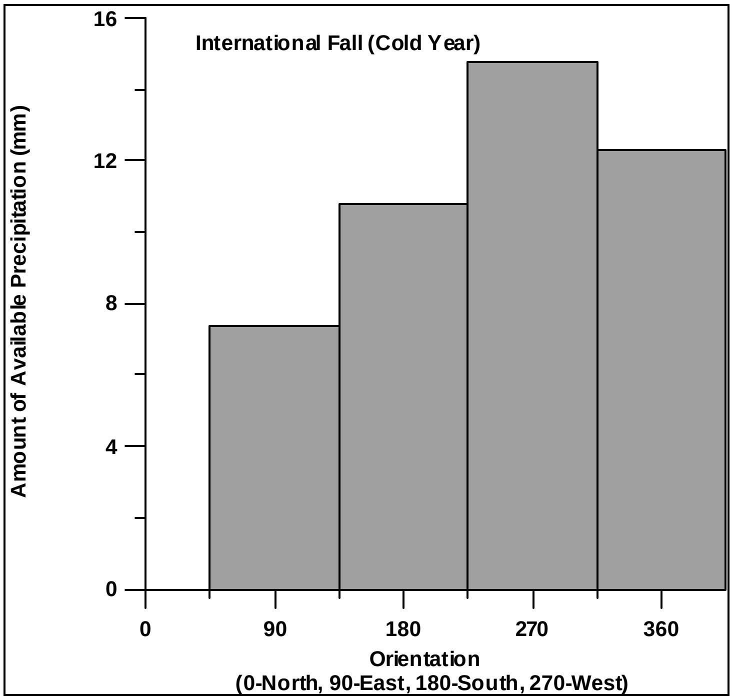


Figure 2.13b: WDR (Wind-driven rain) for International Falls

To establish these values, the following SPC 160P methodology was used.

Proposed ASHRAE SPC 160P Driving Rain Load

Intent

A method to provide an approximation of the magnitude of rainwater deposited on the exterior surface of vertical walls.

Basis

Built upon BS 8104:1992 (EuroNorm pending) and recent research in Europe and North America. Bibliography to follow.

Approach

1. Calculate driving rain free-wind (macro-climate)
2. Modify for exposure effects (meso-climate)
3. Calculate deposition to account for building shape and overhangs (micro-climate)

This approach is intended to be used for hourly meteorological data.

1. Free wind driving rain

Lacy developed a simple approximation of free-wind driving rain (r_v) for a given direction:

$$r_v = 0.222 \cdot V \cdot r_h^{0.88}$$

This is valid at points away from buildings or complex topography. More recent and detailed measurements (Straube 1997) have improved the accuracy of this type of relation by using a more complex equation.

For most purposes under normal exposure conditions, a simple equation of the form

$$r_v = 0.20 \cdot V \cdot r_h.$$

is recommended

2. Exposure Factor

Topography and surrounding buildings can either increase or decrease the driving rain by modifying the wind speed. To account for this effect, it is recommended that an Exposure Factor be applied (Table A1).

Exposure Class	Exposure Factor
Normal	1.0
Exposed (e.g. coastal, hill top site, funneled wind)	1.3
Sheltered (e.g. trees, neighboring bldgs, depression)	0.7

Table A1: Exposure Factor

To account for exposure, the equation from part one

$$r_v = EF \cdot 0.20 \cdot V \cdot r_h$$

where EF is the Exposure Factor

Taller buildings are exposed to higher wind speeds and hence higher driving rain loads. To account for this effect, a Height Factor should be applied. The Height Factor can be calculated from

$$HF(z) = (z/10)^{\alpha}$$

where HF(z) is the Height Factor at a height z (m) above grade,

and α is the gradient exponent, typically 0.10 for open coastal areas, 0.20-0.25 for suburban and as much as 0.4 for built-up urban areas. Reference can be made to any wind load code for more detail.

In lieu of more detailed info, an exponent of 0.25 is recommended.

For low-rise buildings (under 10 m in height, e.g. 2 to 3 stories) the HF=1.0.

Height Above Grade (m)	Height Factor
<10	1.0
20	1.2
50	1.5
>50	Detailed Calculations Recommended

Table A2: Height Factor for Suburban Conditions

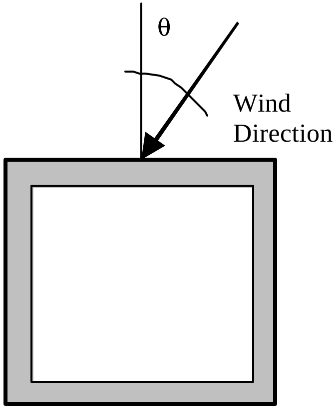
3. Rain Deposition Factor

The orientation of the wall and the shape of the building being considered have a significant effect on how driving rain in the free wind is deposited on the enclosure elements (windows, walls, etc).

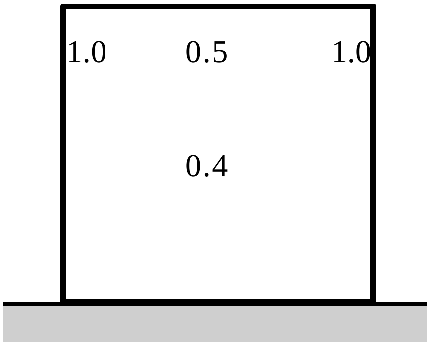
To account for orientation, the cosine of the angle between the wind direction and a line perpendicular to the wall should be applied as an orientation factor.

A Deposition Factor is used to account for the building shape. For a rectangular building with a flat roof, the DF is between 0.3 and 0.5, depending on the location on the wall. In upper corners, the DF can approach 1.0. Note that these Deposition Factors do not account for the response of the wall, e.g., drainage from non-absorptive or saturated surfaces above.

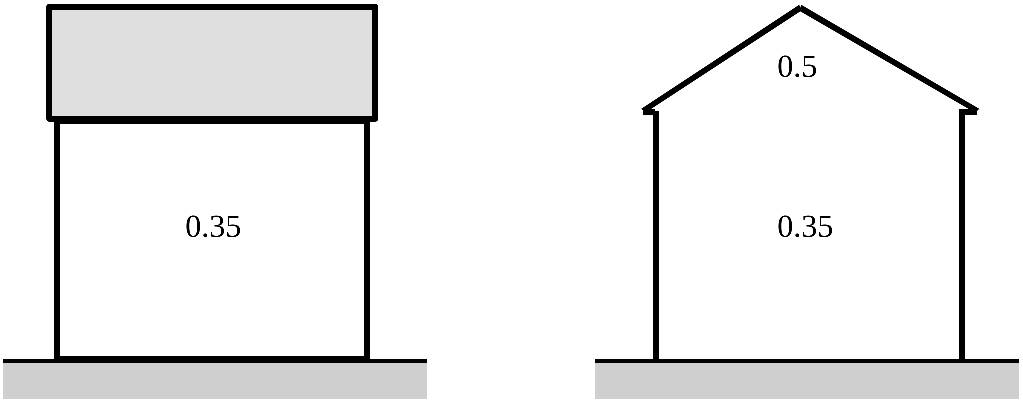
For the gable ends of buildings with pitched roofs, the DF is essentially the same as for a flat roofed building, but without the higher values near the upper corners. For the eaves side of a building with a pitched roof, the DF is 0.5 if the overhang is less than 0.2 m. For overhangs of more than 0.2 m, the DF is reduced to 0.35. (Gutters should be provided to avoid concentration of rainfall off the roof).



Plan View of Building



Flat Roof



Pitched Roof

Deposition Factors for Windward Walls

Hence, the final equation becomes:

$$r_{bv} = EF \cdot DF \cdot HF \cdot 0.20 \cdot V \cdot \cos\theta \cdot r_h$$

where: EF is the Exposure Factor
DF is the Deposition Factor
HF is the Height Factor
V is the hourly average wind velocity at 10 m
θ is the angle between the wind direction and the perpendicular to the wall
r_h is the horizontal rainfall intensity (mm/hr)
r_{bv} is the amount of rain deposition on a vertical wall (kg/m^2/hr)

Appendix A

For tall buildings, the velocity of the free-wind at the height of interest on the building should be accounted for. The wind velocity changes with height according to:

$$V(z) = V_{10} (z/10)^{\alpha}$$

Where: $V(z)$ is the wind velocity (m/s) at a height z (m) above grade,

V_{10} is the velocity at the standard height of 10 m above grade, and

α is the gradient exponent, typically 0.10 for open coastal areas, 0.20-0.25 for suburban and as much as 0.4 for built-up urban areas. Reference can be made to any wind load code for more detail. In lieu of more detailed info, an exponent of 0.2 is recommended.

The adjusted wind velocity, $V(z)$ can be used in lieu of the height and exposure factors (HF & EF). Otherwise, the height correction factor can also be read from Table A1.

Indoor Conditions

The interior environmental conditions in residential buildings are dynamic. Interior conditions change as a function of the operation of the building (mechanical ventilation systems, humidifiers, dehumidifiers, etc.), changes of the exterior climatic conditions, inhabitant activities, plants and the kind of objects placed in the interior environment (moisture storage). Indoor conditions that affect the heat, air, and moisture transport in building envelopes are:

- Temperature conditions
- Moisture content of the air (RH must be used carefully)
- Internal pressures
- Thermal sources
- Moisture sources

In nearly all cases, operation of buildings is better controlled thermally than in any other way. A thermostat is installed in every home, allowing better control of the air space.

A significant amount of moisture can be produced internally, and intentional means of removing that moisture do not exist most of the time. Usually, water vapor is removed by air change: either by natural air leakage through the building envelope or by mechanical ventilation systems. Another mechanism to remove excess water vapor is to employ some kind of dehumidification equipment with designed capacity for interior moisture production loads. The obvious approach to maintain good indoor air quality is to control the level of moisture in the interior air. The most cost-effective way to achieve this is to control moisture at the source.

Sources of Moisture

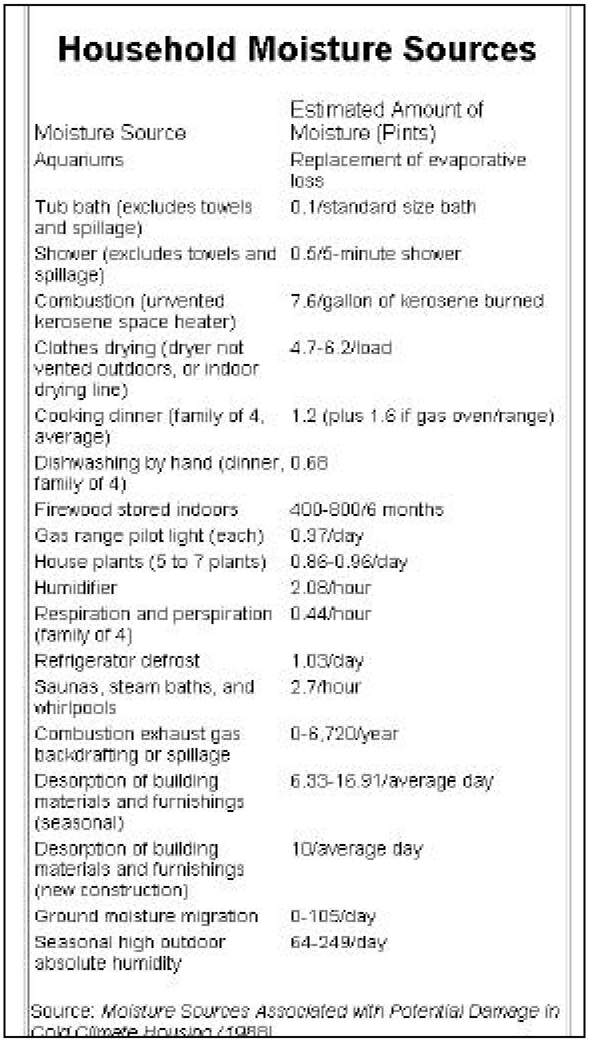
There are many sources of moisture that can increase the amount of water in the building interior. Some of these sources have nothing to do with the general operation of the building, such as the construction moisture content of the building materials, water table level/water and vapor ingress from the ground, and basement and crawlspace walls storing and transporting large quantities of water to the interior. Wind driven rain and water penetration of the building envelope exterior and interior elements may allow seasonal storage effects. Most of the time, each source is independent of the other, but combined together, they may account for significant amount of available water. In Denmark, worked carried out by Kohl (1986), grouped the different sources of moisture production in dwellings as:

- Transpiration from human body
- Evaporation from plants
- Personal hygiene such as bathing
- Cleaning of dwellings
- Washing up
- Laundering and subsequent drying
- Cooking

People as Moisture Sources

Inhabitants and their use of the building may provide a significant amount of water. They may not necessarily be the largest source all the time. Table 3, from a recent publication by LBNL, shows the distribution of moisture loads for various activities in terms of pints of water per day. Figure 2.14 plots out the amount of water that a specific activity may produce, in liters.

Table 3: Moisture Sources



Household Moisture Sources

Moisture Source	Estimated Amount of Moisture (Pints)
Aquariums	Replacement of evaporative loss
Tub bath (excludes towels and spillage)	0.1/standard size bath
Shower (excludes towels and spillage)	0.5/5-minute shower
Combustion (unvented kerosene space heater)	7.6/gallon of kerosene burned
Clothes drying (dryer not vented outdoors, or indoor drying line)	4.7-6.2/load
Cooking dinner (family of 4, average)	1.2 (plus 1.6 if gas oven/range)
Dishwashing by hand (dinner, family of 4)	0.68
Firewood stored indoors	400-800/6 months
Gas range pilot light (each)	0.37/day
House plants (5 to 7 plants)	0.86-0.96/day
Humidifier	2.08/hour
Respiration and perspiration (family of 4)	0.44/hour
Refrigerator defrost	1.03/day
Saunas, steam baths, and whirlpools	2.7/hour
Combustion exhaust gas backdrafting or spillage	0-6,720/year
Desorption of building materials and furnishings (seasonal)	6.33-16.91/average day
Desorption of building materials and furnishings (new construction)	10/average day
Ground moisture migration	0-105/day
Seasonal high outdoor absolute humidity	64-249/day

Source: *Moisture Sources Associated with Potential Damage in Cold Climate Housing* (1988

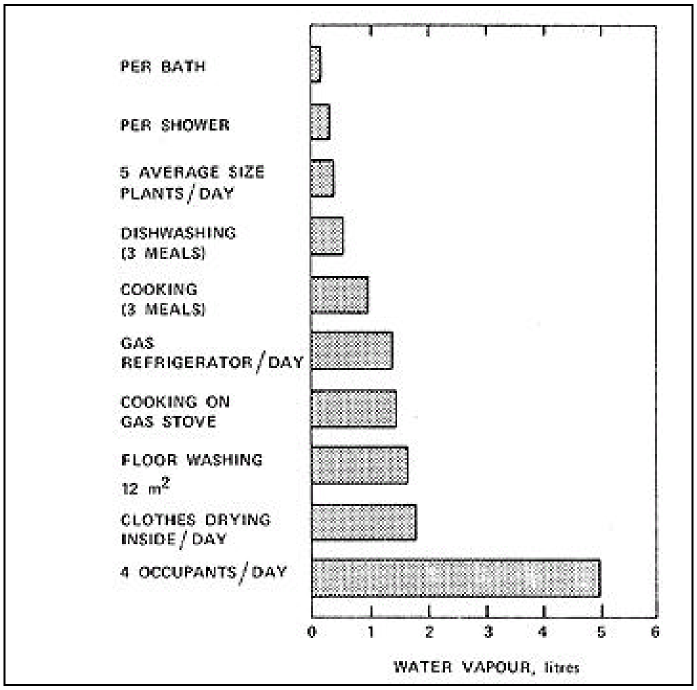


Figure 2.14: Water production (BSI, Richard L. Quirouette)

In general, open literature data for a family of four give values of 3.5 kg/day (7.7 lbs/day) of moisture release from our body, plants contribute 0.46 kg/day (1.0 lb/day), personal hygiene about 0.5 kg/day (1.1 lb/day) (family of four about 1.3 kg/day or 2.9 lbs/day), contributions due to house cleaning about 0.2 kg/day (0.4 lb/day), washing up approximately 0.4 kg/day (0.9 lb/day), laundry and drying anywhere from 0.1 kg/day to 1.8 kg/day (0.2-4.0 lbs/day), cooking approximately 0.897 kg/day (2 lbs/day). If these are all summed up, a typical family of 4 may produce 4 to 14 kg/day (9-31 lbs/day) of moisture. This numbers can be compared to numbers given by NRCan, for a typical household, four people of up to 160 liters (42 gallons) of water into the air each month. Add to that other common sources of moisture—from long showers to leaky plumbing—and it's easy to see how homes can suffer from poor air quality and major structural problems due to excessive moisture. In addition, health experts know that fungi, mold, and dust mites flourish in damp areas and can cause health problems such as allergies and asthma. Having the right moisture level in one's house means greater energy fitness, savings in home repairs, and better health for years to come.

Gas appliances can release up to 1.3 kg/day (3 lbs/day), saunas and hot tubs can also release significant amounts of water to the inside of the house, as can drying of firewood indoors.

How is the interior environment affected in Minnesota?

Indoor Conditions

The interior environmental conditions in residential buildings are dynamic. Interior conditions change as a function of the operation of the building (mechanical ventilation systems, humidifiers, dehumidifiers, etc.), changes of the exterior climatic conditions, inhabitant activities, plants and the kind of objects placed in the interior environment (moisture storage). A significant amount of moisture can be produced internally and a means of removing that moisture should exist. Usually water vapor is removed by air change, either by natural air leakage through the building envelope or by mechanical ventilation systems. Another mechanism to remove excess water vapor is to employ some kind of dehumidification equipment with designed capacity for interior moisture production loads. The obvious approach to maintain good indoor air quality is to control the level of moisture in the interior air. The most cost-effective way to achieve this is to control moisture at the source.

ASHRAE recommends that indoor temperatures during the winter months be maintained between 68 and 75° F and indoor temperatures during the summer months should be between 73 and 79° F. In practice, complaints may occur with any temperature not maintained at 72° F with some air circulation. Relative humidity (RH) measures the amount of moisture in the air; ASHRAE recommends RH be maintained between 30% and 60% for indoor environments. RH below 30% can cause drying of the mucous membranes and discomfort for many people. RH above 60% for extended time periods promotes indoor microbial growth.

HVAC systems are designed to supply fresh air into the occupied space, supplying fresh air into the building and diluting contaminants and therefore preventing buildup. ASHRAE specifies the minimum amount of outside air supplied to an occupied building as 20 cubic feet per minute (CFM) per person in each occupied zone. If the HVAC system is shut down overnight, the system should be started at least one hour before occupancy to provide adequate ventilation. Other contributors to stale and poorly mixed air include poor location of supply and exhaust air diffusers, improper building or system design (often caused by change of building occupancy from original design configuration with inadequate attention during remodeling), or indoor structures that prevent free movement of air.

Carbon monoxide (CO) is a common result of the presence of or proximity to sources of combustion. It is present to some degree whenever fuel-operated systems are used. High levels are an immediate threat to life. Lower levels are a cause for health concern. Concentrations should be maintained as close to undetectable as possible.

Interior Environment Approach (This Project)

INTRODUCTION

A recent paper (TenWolde and Walker, 2001) describes a state-of-the-art methodology to obtain the interior environmental conditions in terms of an analysis approach and design values. Hygrothermal models require the inputs of interior environmental conditions, and are extremely sensitive to the assumed moisture boundary conditions. For instance, during winter, the moisture conditions in walls depend greatly on the indoor humidity conditions (TenWolde et al. 1995). Thus, a consistent approach to moisture design demands a consistent framework for design assumptions, or assumed "loads." The question whether or not design features such as vapor retarders or ventilation systems are necessary cannot be answered unless there is a consensus definition of the interior and exterior moisture boundary conditions that the building is expected to be able to sustain without negative consequences to itself or its inhabitants. No standardized methodology for moisture design exists as yet, but ASHRAE Standard Committee 160P, *Design Criteria for Moisture Control in Buildings*, is attempting to formulate appropriate design assumptions for moisture design analysis and criteria for acceptable performance. The ASHRAE 160P committee is trying to arrive at design loads despite a general lack of data and information. The committee is formulating several research projects to obtain better data, and they will recommend these projects for funding by ASHRAE.

According to TenWolde and Walker (2001) the SPC 160P standard will include interior design loads (temperature, humidity, and air pressure) as well as exterior design loads (temperature, humidity, and rain). Although it is common to impose very stringent criteria for structural design because of safety concerns, moisture damage usually occurs over a long period of time and usually has less disastrous, although sometimes costly, consequences. A consensus is beginning to emerge that a 10% likelihood of failure is an appropriate level in building moisture design analysis, and we will use this for the purposes of this paper. The definition of failure will also be addressed in ASHRAE Standard 160P.

In a moisture analysis for building envelope design, the choice of indoor environmental conditions is extremely important, especially for buildings in cold climates. Several European countries have defined Indoor Climate Classes. For instance, Tammes and Vos (1980) describe four climate classes for use in the Netherlands based on interior vapor pressure ranges. This approach requires a different definition for each climate and does not account for large seasonal changes. Sanders (1996) and the IEA Annex 24 take a different approach and define four climate classes on the basis of three critical indoor vapor pressures or "pivot points." These pivot points are related to the occurrence of condensation in a north-facing wall, net annual moisture accumulation in a north-facing wall, or net annual moisture accumulation in a flat roof. These pivot points depend on construction and climate.

According to TenWolde and Walker (2001), the approached favored within SPC 160P is to be independent of construction type but will include the influences of ventilation and air-conditioning equipment, as well as controls that may or may not be part of the building design. In residential buildings in Minnesota, indoor humidity is rarely explicitly controlled. During winter conditions, the indoor humidity depends on a combination of sources (such as people and foundation moisture) and building ventilation. In some extreme climates (such as Minnesota), houses are humidified during the winter. In that case an estimate must be made for this additional moisture generation rate. For summer conditions, there is the added complication of air conditioner and dehumidifier operation for the whole house or individual rooms. Unfortunately, the moisture removal performance of these devices is highly variable and depends on a host of factors that cannot easily be dealt with during the design process.

DESIGN INDOOR HUMIDITY FOR HEATING

Humidity of indoor air is the result of a balance between moisture gains, moisture removal from the building, and net moisture exchange with hygroscopic materials inside the building. TenWolde (1994a, 1994b) showed that moisture storage in residences stabilizes the indoor humidity, and that daily or even weekly averages can be used for the purpose of building moisture analysis. Ignoring storage and using time-averaged values for the other parameters allows the determination of the indoor vapor pressure:

$$P_i = P_o + \frac{P_{atm} m_s}{0.62198 m_v} \tag{1}$$

where P_i = indoor vapor pressure, in. Hg (Pa)
P_o = outdoor vapor pressure, in. Hg (Pa)
P_{atm} = atmospheric pressure, in. Hg (Pa)
m_s = moisture source rate, lb/h (kg/s)
m_v = ventilation rate, lb/h (kg/s)

The ventilation rate for residential buildings is often expressed in terms of air changes per hour, rather than as a mass flow rate. The mass flow rate can be obtained from the air change rate using Equation 2:

$$m_v = \frac{rVI}{n} \tag{2}$$

where ρ = air density, lb/ft^3 (kg/m^3)
V = building volume, ft^3 (m^3)
I = air exchange rate, 1/h
n = 1 in IP units, 3600 s/h in SI units

Combining Equations 1 and 2 with the assumption of a standard atmospheric pressure of 29.9 in. Hg (101.3 kPa) and air density of 0.075 lb/ft^3 (1.2 kg/m^3) yields a simple equation:

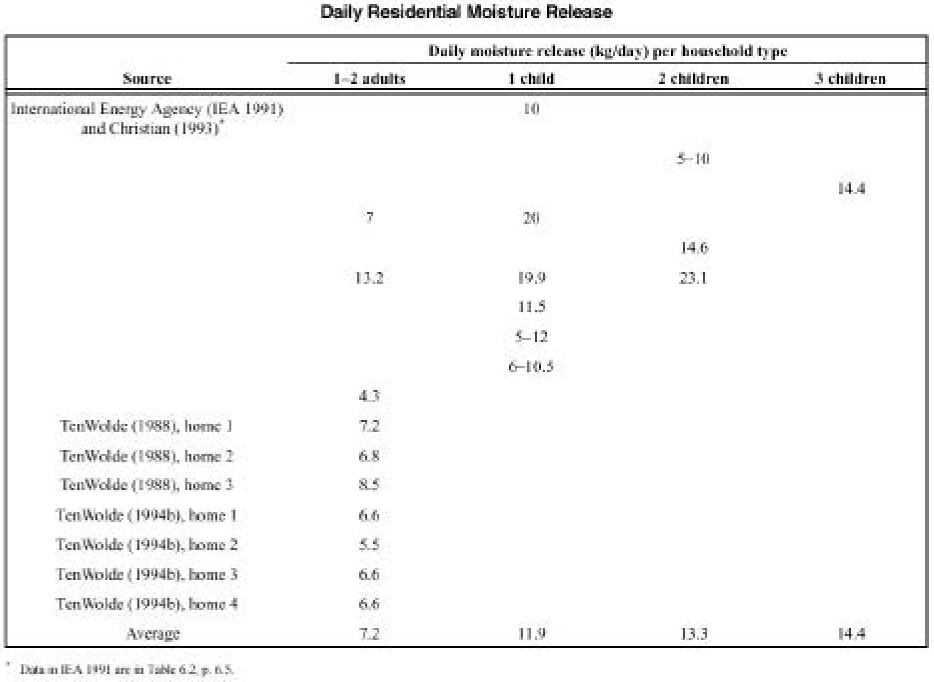
$$p_i = p_o + \frac{cm_s}{VI} \qquad (3)$$

where c = 641 in. Hg ft^3/lb (4.89 × 10^5 m^2/s^2).

The moisture source term in Equation 1 includes both generation (e.g., people) and dehumidification. If dehumidification exceeds the rate at which moisture is added, this term becomes negative. In this project, we adopted the equations above, but also accounted for the transient moisture capacity of the air. The air was allowed to be influenced by the previous hour condition. In addition, humidification was allowed to bring the relative humidity to either 15% or until surface condensation appeared on a window with a U value of 0.35 (IP). While it is well understood that windows have a multi-dimensional distinct distribution of heat flow, this uniform U value approach of 0.35 allowed additional sophistication than that proposed in the ASHRAE 160P Standard, and is expected to give values that are a closer representation to reality. It is a fact that people limit/control their humidification system whenever vapor condenses on windows.

Table 4 shows measured and established data from Christian (1993) and TenWolde (1988, 1994). In this project, three floor areas were used: 1400 ft^3, 2000 ft^3 and 2457 ft^3. The two exterior climates (International Falls and Minneapolis) were entered into existing software developed at ORNL that determines the interior environmental conditions.

Table 4: Daily Moisture Production (TenWolde and Walker, 2001)



Daily Residential Moisture Release

	Daily moisture release (kg/day) per household type			
Source	1–2 adults	1 child	2 children	3 children
International Energy Agency (IEA 1991) and Christian (1993)*		10		
			5–10	
				14.4
	7	20		
			14.6	
	13.2	19.9	23.1	
		11.5		
		5–12		
		6–10.5		
	4.3			
TenWolde (1988), home 1	7.2			
TenWolde (1988), home 2	6.8			
TenWolde (1988), home 3	8.5			
TenWolde (1994b), home 1	6.6			
TenWolde (1994b), home 2	5.5			
TenWolde (1994b), home 3	6.6			
TenWolde (1994b), home 4	6.6			
Average	7.2	11.9	13.3	14.4

* Data in IEA 1991 are in Table 6.2, p. 6.5.

Figures 2.15 through 2.20 show the influence of ventilation on the interior conditions for the city of Minneapolis MN, for three seasons. Winter, spring, and summer conditions were investigated for the corresponding months of January, April, and July.

Figures 2.15, 2.17, and 2.19 show average monthly local temperatures and relative humidity for a period of 30 years. Figures 2.16, 2.18, and 2.20 show the interior relative humidity as a function of RH and 3 levels of moisture production rates of 5kg/day, 10kg/day and 20kg/day (1.3, 2.6, and 5.3 gal/day). The setpoint temperature and relative humidities were chosen from the 30 year average conditions shown in Figures 2.15, 2.17, and 2.19.

For a residence of 2457 ft^2, it is evident that in January, with the exception of a very low moisture production rate of 5 kg/day, the interior relative humidity can be high enough to lead to mold growth on wall surfaces and condensation on windows. At a ventilation rate of 0.25 ACH, center of room relative humidities easily exceed 40%. This will result in condensation on typical glazing, and result in mold growth at exterior walls where the gypsum board surface RH will exceed 80%. However, at a ventilation rate of 0.35 ACH, interior relative humidities will remain in the 20 to 30% range, avoiding window condensation and mold. However, with typical building envelope tightness, average air change rates of 0.35 ACH cannot be achieved. Similar behavior is demonstrated for April where even higher interior relative humidities were found.

From these results, one can observe that under normal building operating conditions with a family of 4, the interior relative humidity becomes prohibitively large without an appropriate mechanical ventilation system that maintains ACH rates at 0.35 (for a large part of the year).

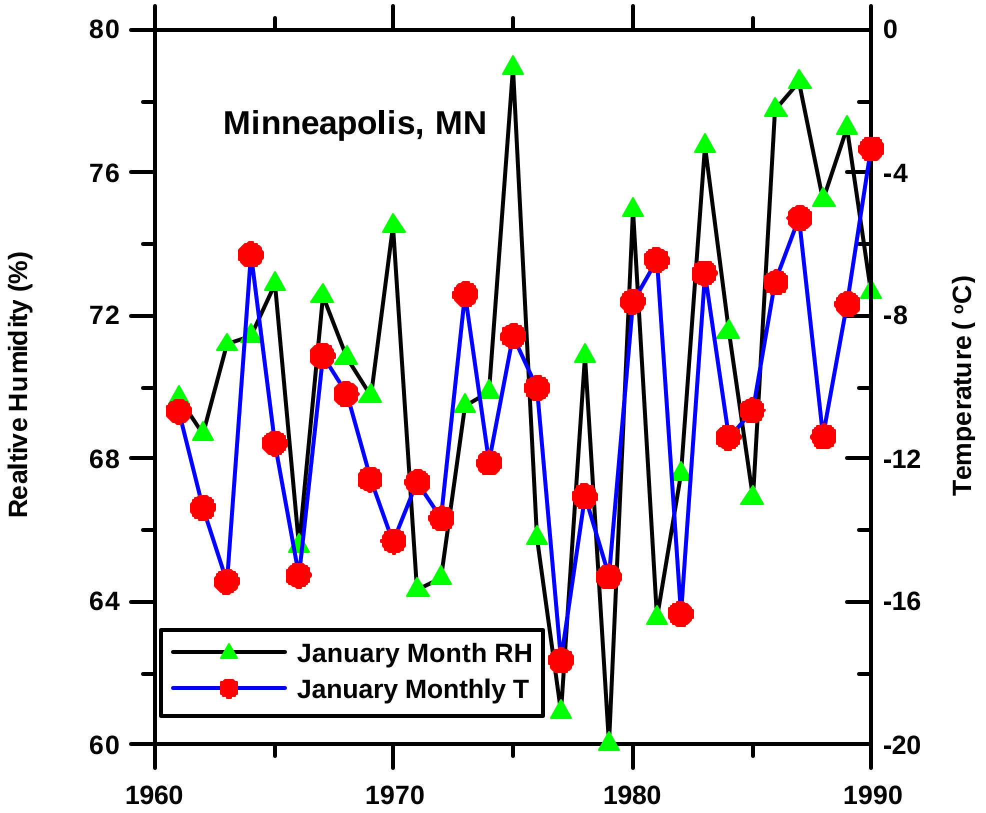


Figure 2.15: Monthly Average Exterior T and RH for January (Minneapolis)

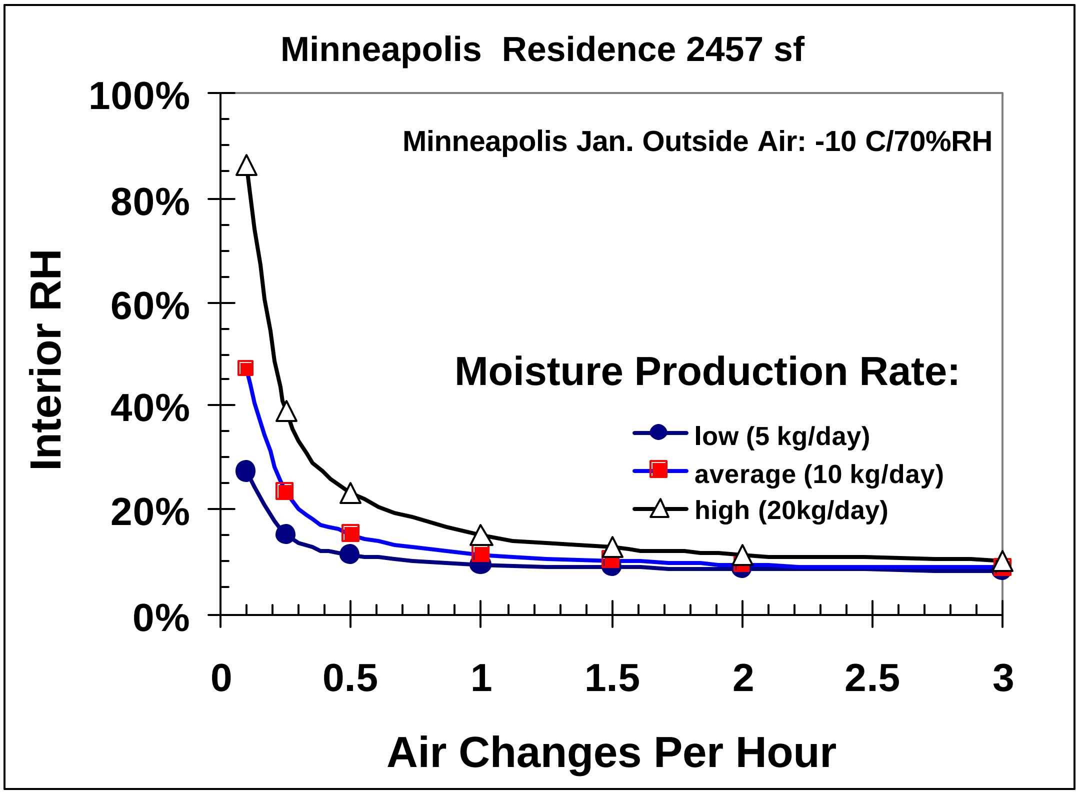


Figure 2.16: Effect of Ventilation and Moisture Production on Interior RH (January)

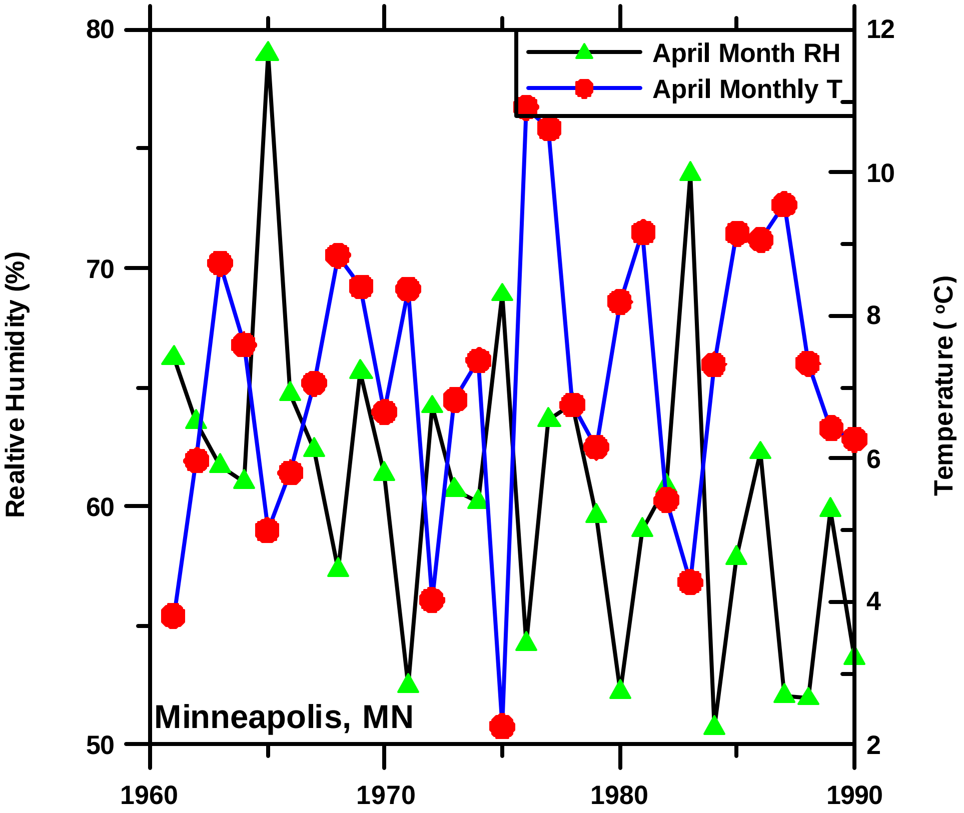


Figure 2.17: Monthly Average Exterior T and RH for April (Minneapolis)

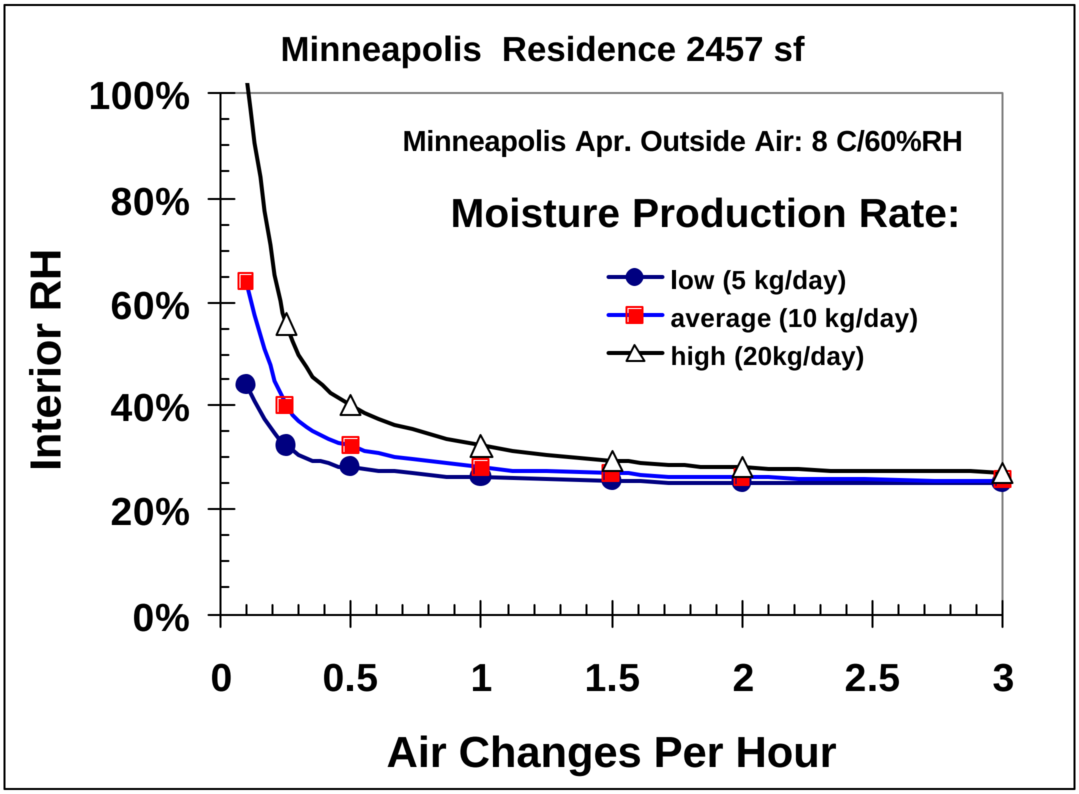


Figure 2.18: Effect of Ventilation and Moisture Production on Interior RH (April)

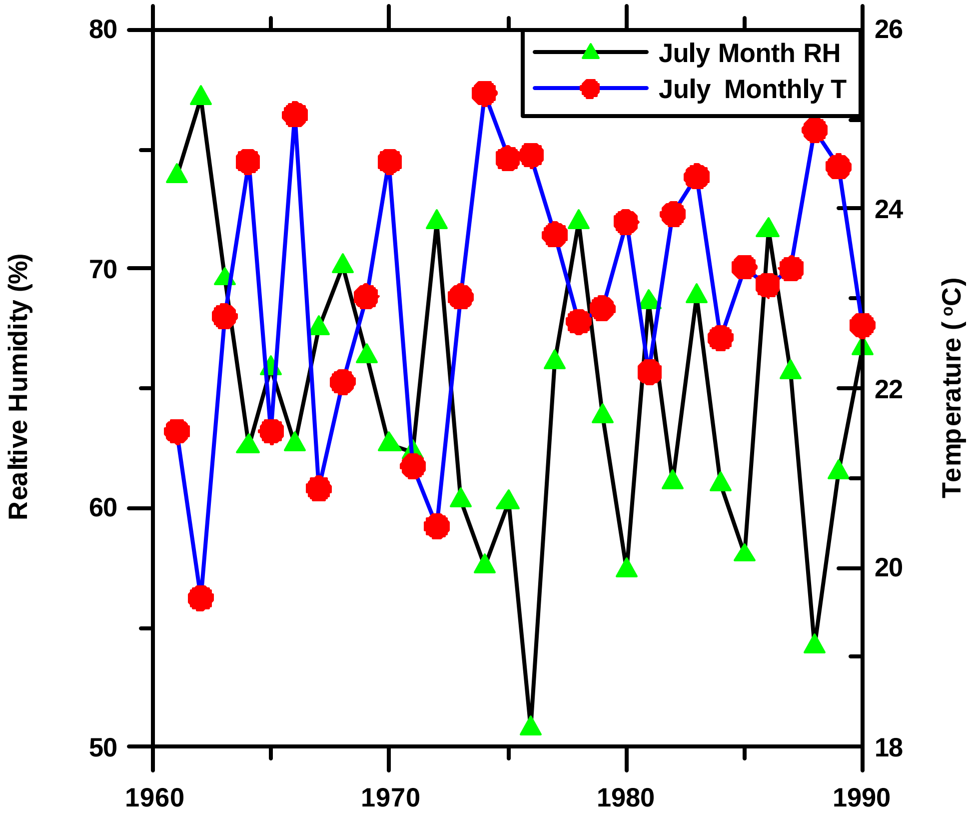


Figure 2.19: Monthly Average Exterior T and RH for July (Minneapolis)

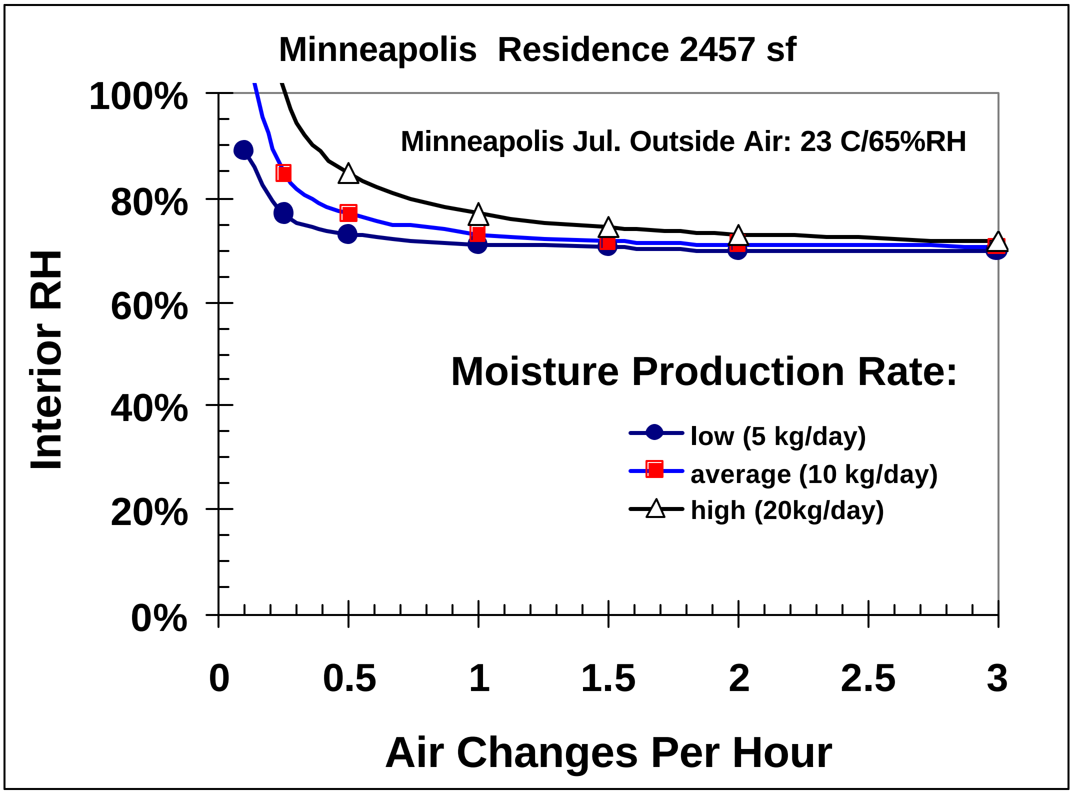


Figure 2.20: Effect of Ventilation and Moisture Production on Interior RH (July)

In Figures 2.21 through 2.24, the corresponding instantaneous values of the interior RH versus time in hours (0 is January) is plotted out for a period of two years (10% cold and 10% hot year). The moving average is shown as a weekly averaged number every 168 hours (7 days). Results clearly show the effects of moisture source rates and air exchange rate. Permeable wall systems (Category 2) here are shown to not be able to appropriately dilute the moisture production rates of a family of 4.

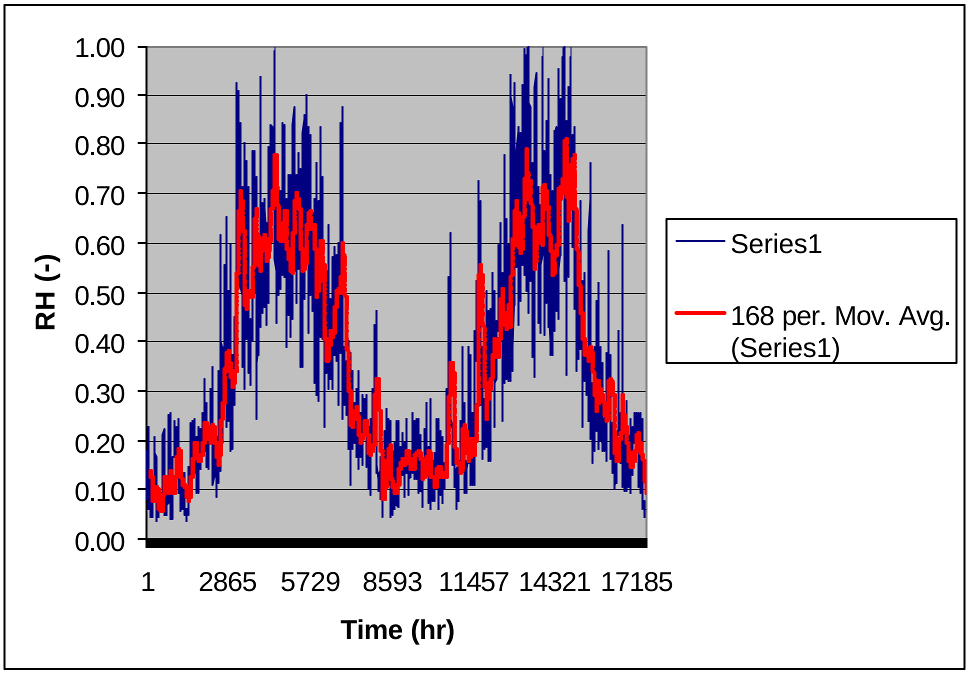


Figure 2.21: Interior RH (Minneapolis) w. 5 kg/day moisture source (3 ACH)

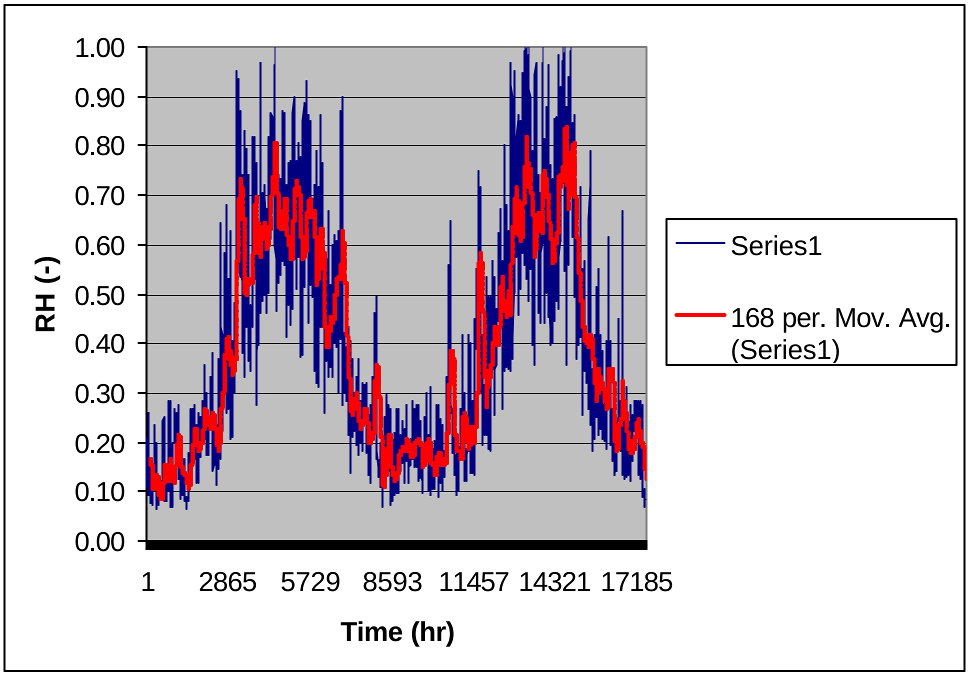


Figure 2.22: Interior RH (Minneapolis) w. 5 kg/day moisture source (0.35 ACH, 1 g/m^3)

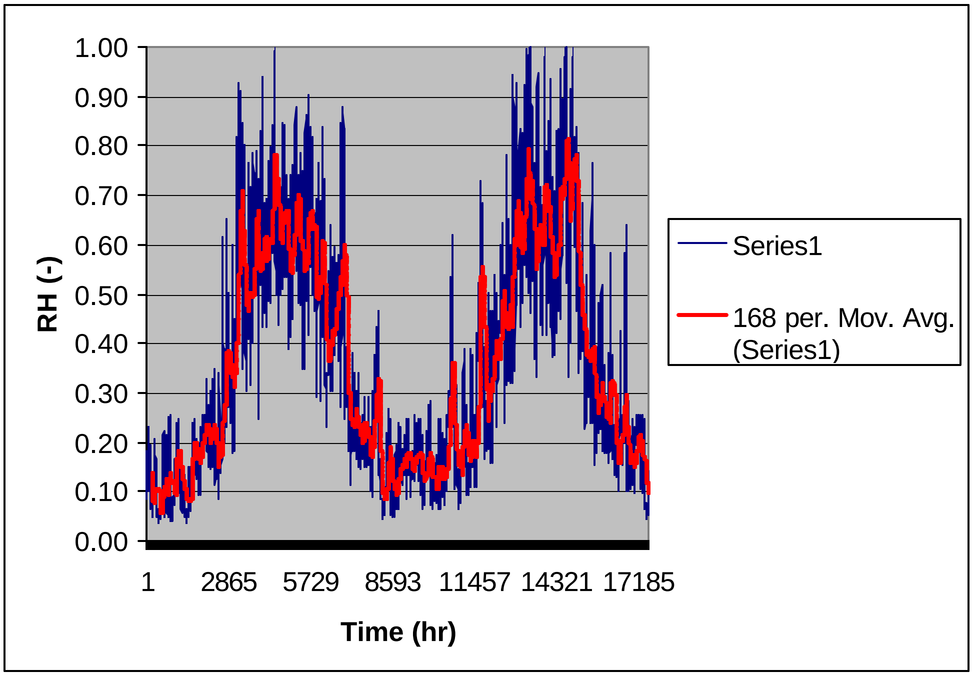


Figure 2.23: Interior RH (Minneapolis) w. 20 kg/day moisture source (3 ACH)

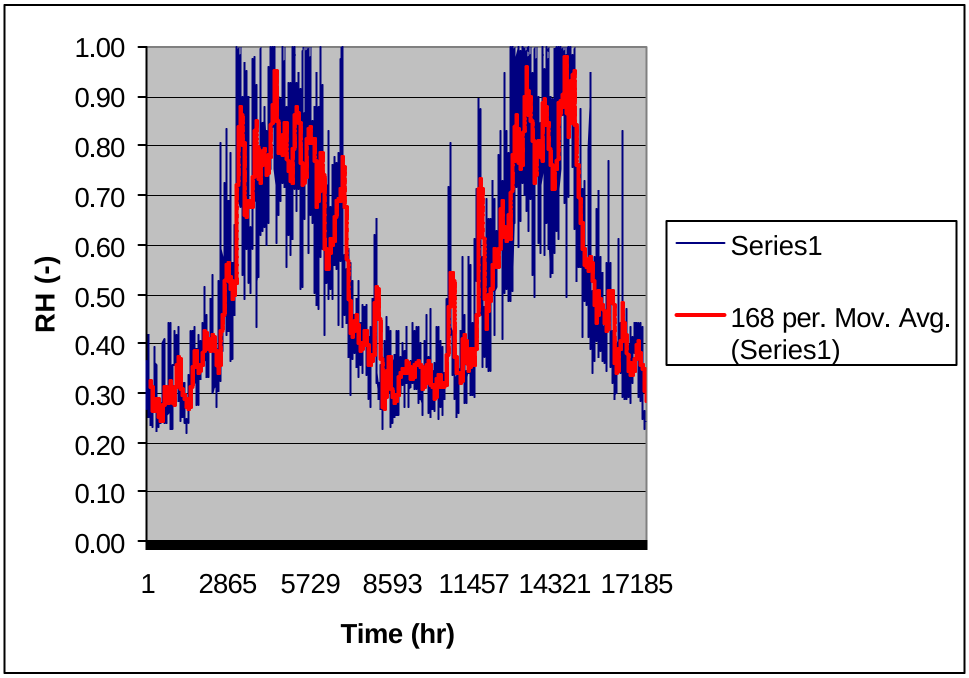


Figure 2.24: Interior RH (Minneapolis) w. 20 kg/day moisture source (0.3 ACH, 4.17 g/m)

List of Figures

List of Tables