Acceptable Air Tightness of Walls in Passive Houses

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1 Introduction

It has long been known that air-tightness is a critical element of a passive building, for two reasons. One is that super-insulation can only do so much to improve the energy performance of a building while the heat losses from air infiltration remain uncontrolled. The other is that air leaks can cause moisture problems / damage, and more-insulated assemblies are fundamentally more susceptible to such problems due to decreased heat flux, which lowers the rate of drying. (Nisson & Dutt 1985, LePage et al 2013)

When it comes to setting guidelines and standards for air-tightness, there has been a range of recommended performance thresholds, historically and in current practice. For example:

- 1-3 air changes per hour at 50 Pascals pressure difference (ACH50) in the detached house residential context (Nisson & Dutt 1985),
- 1.5-3 ACH50 (climate zone dependent) in the current DOE Zero Energy Ready Home requirements (rev. 05),
- 0.6 ACH50[1] under the standards of the Passivhaus Institut (PHI),
- 0.25 cfm at 75 Pascals pressure difference (cfm75) per ft2 of enclosure (all 6 sides) in the U.S. Army Corps of Engineers protocol (version 3, 2012),
- 0.4 cfm75/ft2 of enclosure in the U.S. General Services Administration P100 facilities standards (2015) at the “baseline” level, and 0.10 cfm75/ft2 at the Tier 3 High Performance level.

The Air Barrier Association of America (ABAA) has set requirements for air barrier materials and assemblies. The air barrier materials should not have more than 0.004 cfm/ft2 air leakage at 75 Pa and the air barrier assemblies (such as walls) should not leak more than 0.04 cfm/ft2 at 75 Pa.

Consider how that translates into ACH50. Suppose a two-story home with 2400 square feet of conditioned floor area (exterior dimensions) - 27 feet wide, 44 feet long, and 18 feet high. The envelope area is then 2*(27*44+27*18+44*18)=4932 ft2. The interior air volume can be estimated as 2*(25*42*8) = 16800 ft3

If the air barrier assemblies meet the ABAA definition, the leakage just through those assemblies would be 0.04 cfm75/ft2 * 4932 ft2 = 197 cfm75 or 11837 ft3/h. In terms of air changes per hour that is (11837 ft3/h)/(16800 ft3/AC) = 0.70 ACH75.

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[1] Based on interior air volume, rather than gross building volume.

Now adjust that to 50 Pascals assuming a power law for flow rate:

$$Q = K*dP^n \tag{1}$$

where Q = flow rate, K = flow coefficient, n = flow exponent (0.5-1.0), and dP is the test pressure. Then

$$Q50/Q75 = (50/75)^{(0.5\ \text{to}\ 1)} = 0.67\ \text{to}\ 0.8,$$
$$\text{and therefore } 0.7\ \text{ACH75} = 0.47\ \text{to}\ 0.57\ \text{ACH50}. \tag{2}$$

For this size of building, the leakage just through the air barrier assemblies would therefore approach the allowed limit under PHI's standard. Because air leaks in residential buildings have other possible paths and only a fraction of the whole-house leakage finds its way to the insulated cavities, it must be the case that if this house were to test at 0.6 ACH50, the air-tightness of the walls must be *better* than 0.04 cfm75/ft2, perhaps by a factor of two. (See Appendix B.)

The question addressed in this paper is, does that increased tightness significantly lower the moisture risk? To put it another way, setting an air-tightness criterion for the whole building at 0.08 cfm75/ft2, so that the assembly air leakage is about 0.04 cfm75/ft2, would for these kinds of buildings be a more relaxed standard than 0.6 ACH50 (though still stricter than GSA Tier 3) - does that significantly increase the moisture risk?

Accordingly, this study shows the energy and moisture performance of highly insulated walls with air leakage rates through the insulated cavities of 0.01-0.04 cfm/ft2 at 75 Pa, for a number of different climates.

The wall assembly is fixed and intentionally of a non-ideal double-stud design in order to create some sensitivity. It would not actually be a good idea to build it in all climates. For the question of interest here, the relative performance between the different air tightness levels is more telling than the absolute numbers.

2 Approach

A two-dimensional heat, air and moisture transport simulation model was used to analyze wall systems with air flow through the insulated cavity in various different climates. This software includes the transport physics as described by WUFI-2D with the addition of the air flow equations as provided by LATENITE and MOISTUREXPERT both described in the ASTM

Manual 40. The airflow paths were created based on detailed measurements of air leakage characteristics of joints between wall components (Wolf & Tyler 2013)

The locations evaluated with the simulation model were: Atlanta (GA), Baltimore (MD), Boston (MA), Houston (TX), Minneapolis (MN), Seattle (WA) and Fairbanks (AK) covering climate zones from hot and humid to very cold.

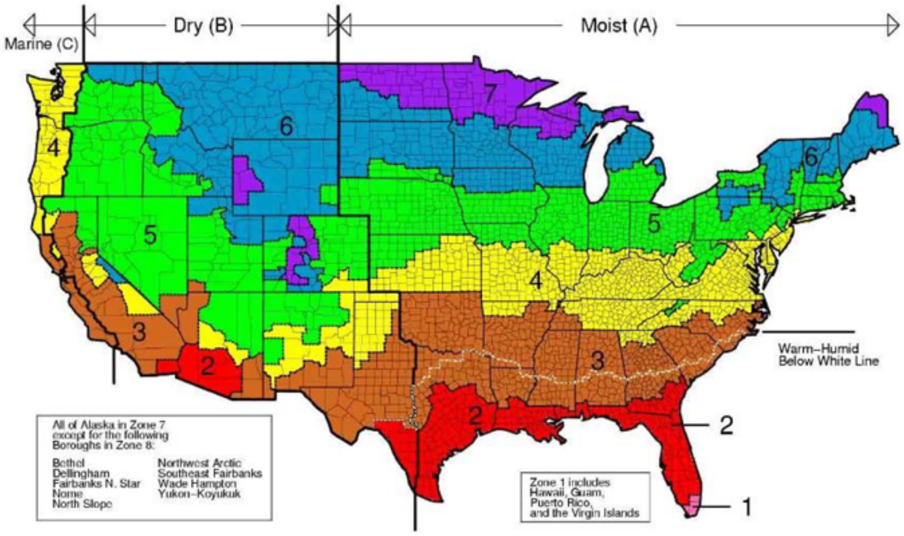

Figure 1. IECC 2009 Climate Zones.

Table 1. Locations and their climate zones.

Location	**Climate Zone (location in map in** Error! Reference source not found.**)**
Houston, TX	2A (G)
Atlanta, GA	3A (A)
Baltimore, MD	4A (C)
Seattle, WA	4C (E)
Boston, MA	5A (B)
Minneapolis, MN	6A (D)
Fairbanks, AK	8B (F)

3 Simulated Structure and Environmental Loads

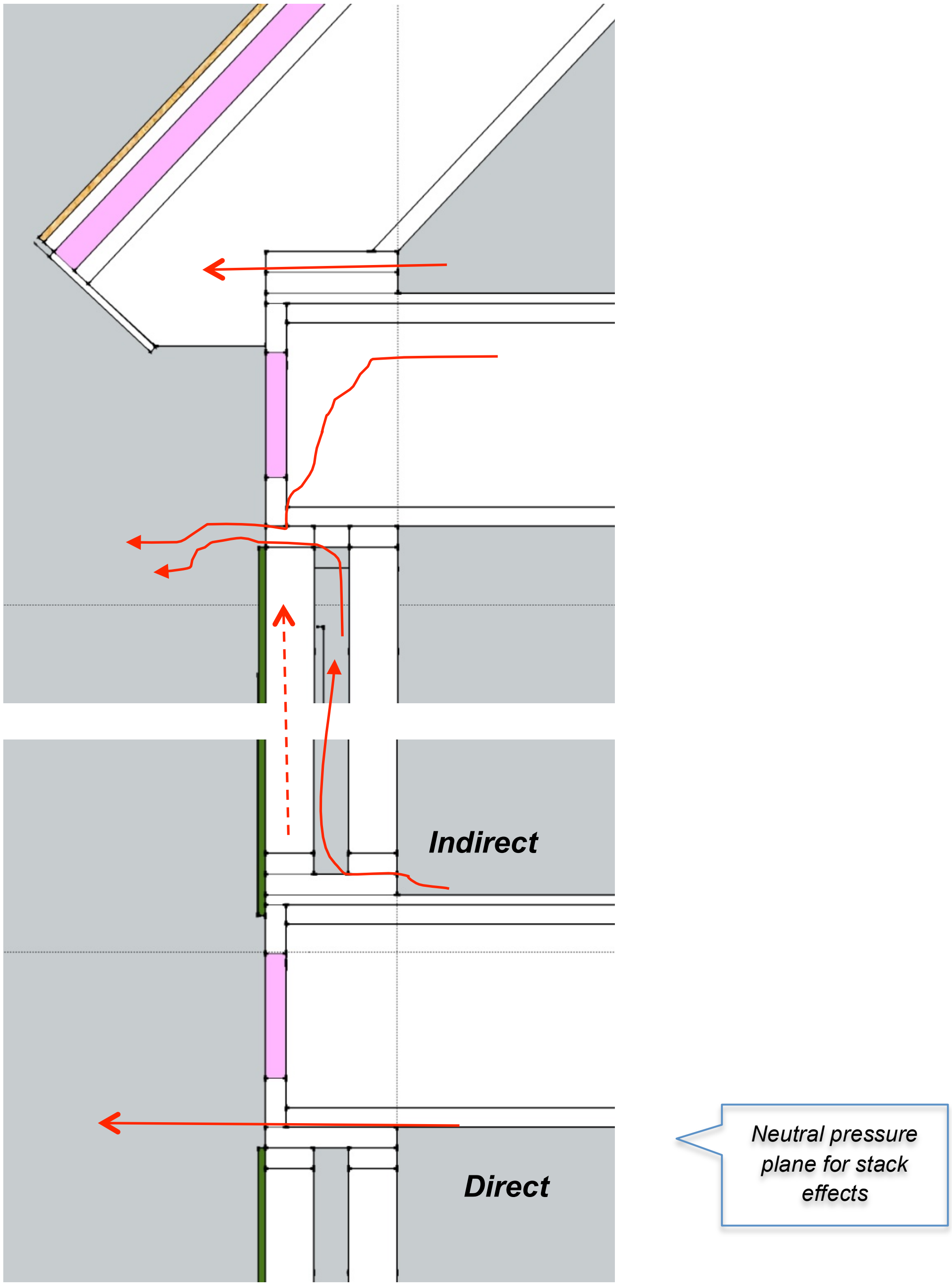

Figure 2. Simulated wall system (double stud wall) with potential air leakage paths shown. Interior drywall is not shown.

The simulated wall system is the wall section from subfloor to the top plate of the second floor as shown in Figure 3. Some of the typical air leakage paths are shown. The airflows are affected by air pressures caused by mechanical pressures, wind and stack effects. The neutral plane for stack effects in the simulations is assumed to be at the top plate height of the first floor.

Interior moisture loads (absolute humidity difference between indoor air and outdoor air in g/m3) were calculated based on ASHRAE standard 160. Loads were calculated assuming 11 L/day (24 lb/day) moisture production, in a four-bedroom house with a volume of 17553 cf and a natural ventilation rate 0.25 ach (leakage and occupancy effects combined). These result in a moisture load of +3.6 g/m^3 or about 500 Pa higher vapor pressure indoors than outdoors when no dehumidification by cooling system is present. The moisture performance of the wall is critically affected by not only the air tightness rating but also by the pressure conditions in the house and by the indoor and outdoor moisture content of air. Especially when condensation of water vapor inside the wall is of concern the indoor humidity plays a deciding role when the conditions inside the wall allow for moisture accumulation. The control and balancing of ventilation is important in a tight house to make sure that the house is not over pressurized during cold weather.

3.1 Wall System

The wall system consisted of the following layers:

1. Vinyl siding
2. ¾" (19 mm) air cavity
3. highly permeable water resistive barrier (50+ perms)
4. 7/16" OSB
5. 10" double-stud cavity with Fiberglass insulation
6. 1 perm vapor retarder
7. 1/2" Gypsum board with 10 perm paint.

The wall was oriented north.

4 Results – Air leakage Rates and Indoor Moisture Loads

Full results for different climate zones are shown in the end of the report. Results for Baltimore (MD) are used as an example and discussed here in more detail. The moisture loads and indoor temperature and relative humidity are shown in Figure 3 for Baltimore MD.

Air leakage through the wall (shown in Figure 5) varies as a function of pressures that are affected by mechanical pressures, stack effect and wind (and leakage paths). In these simulations stack (temperature difference) caused only a minor effect on the airflow rates due to the location of the air leak paths with respect to neutral plane.

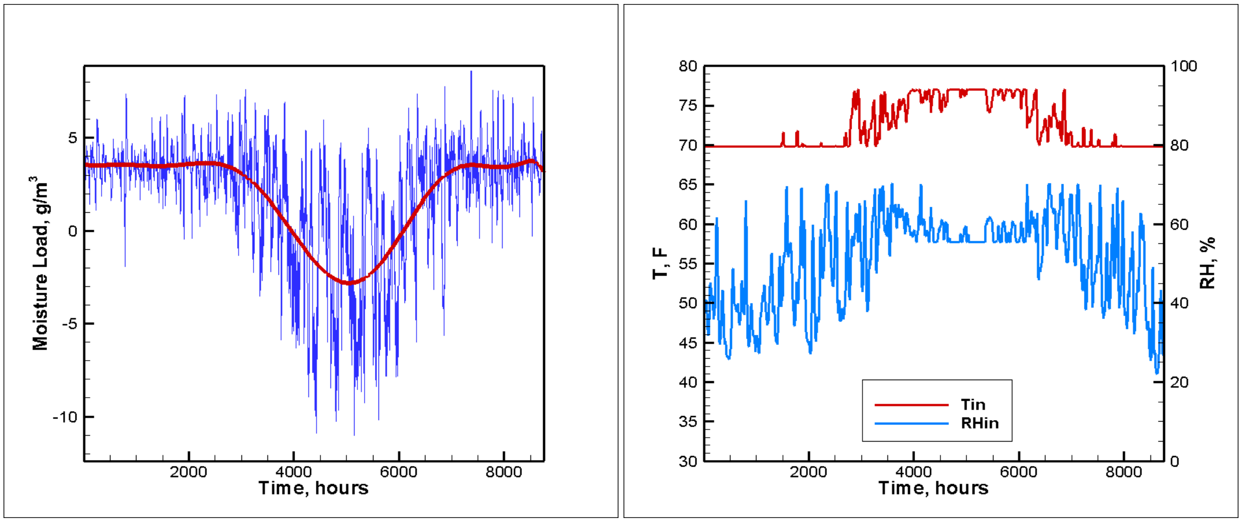

Figure 3. Indoor moisture load (left) and indoor temperature (°F) and relative humidity (%) as a function of the hour of the year starting January 1. Conditions were calculated according to ASHRAE Standard 160. Cooling in the summer reduces the indoor moisture load.

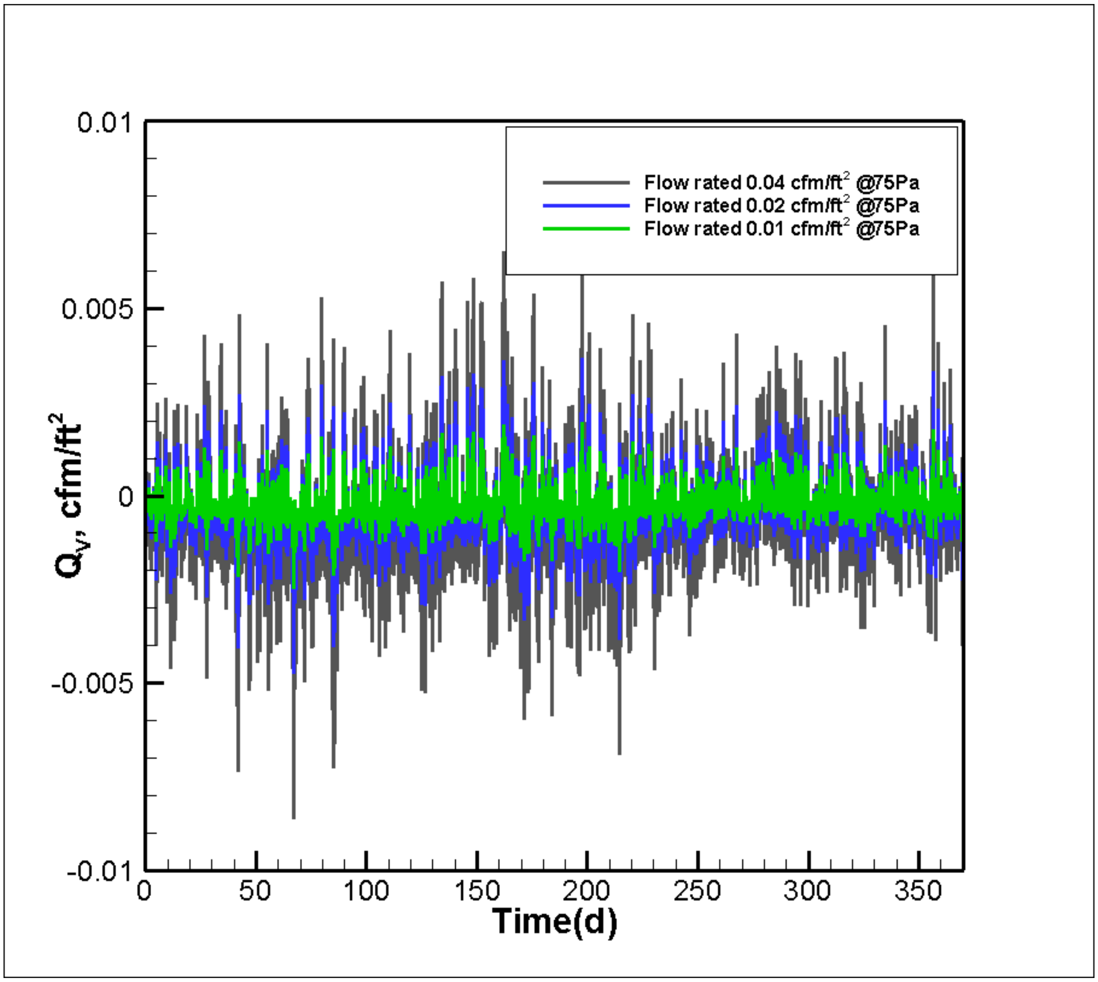

Figure 4. Hourly air leakage rate through the wall (cfm/ft^2) for a full year starting October 1st.

5 Energy Performance

Air leakage causes heat loss (or gain depending on the climate). When the air leakage is not a direct path through the wall but instead the air flows through the insulated cavity then the wall system can act as a heat recovery device (Timusk et al, 1987, Morrison et al, 1992). Figure 5 shows the annual heat loss in Baltimore and the split between conduction and air leakage heat loss as calculated based on the heating season heat fluxes for the wall in the study. The energy loss obviously becomes smaller as the air leakage rates become lower but at the same time, the heat recovery rates (as percentage recovered) on the airflow become slightly higher.

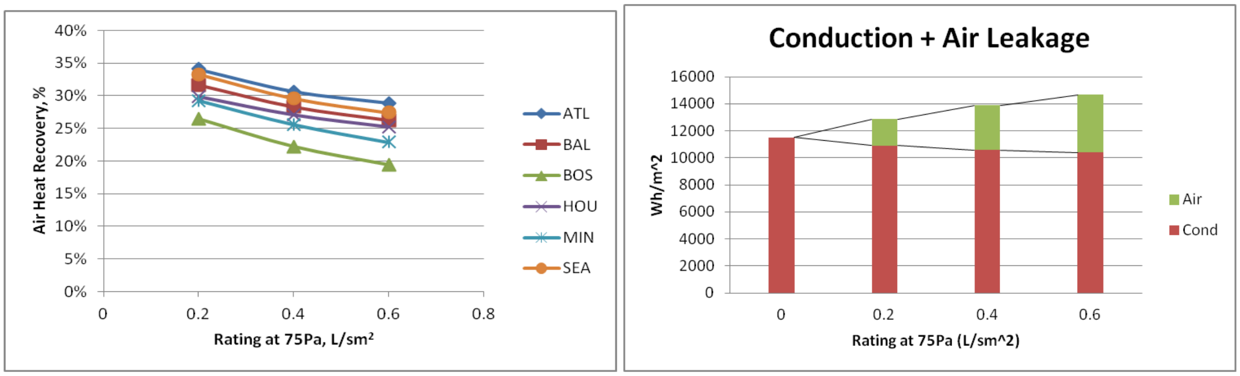

Figure 5. Heat recovery effect in air flowing through an insulated wall cavity (left). The higher the air leakage through the wall the lower the heat recovery. The heat recovery effect is visualized on the right chart which shows the total energy loss throughout the year and the split between conduction and air leakage. The conduction heat loss is reduced when more air flows through the wall (air flows were mostly exfiltration). (Note: 0.2 cfm/ft^2 ≈ 1 L/s,m^2). Energy balance boundary is on the interior surface of the wall.

When air is leaking through a wall cavity it is releasing or gaining heat depending on the temperatures of air and the porous material. The airflow thus affects how much heat is lost by conduction. If air is leaking out through the wall in cold climates (exfiltration) then the warm interior air is warming up the wall thus reducing the conduction heat loss through the surface of the wall on the indoor side. On the exterior side of the wall, the conduction loss is increased by the airflow and thus it is important to be consistent in the selection of control boundary for heat flows.

The walls with air leakage characteristics of 0.04 cfm/ft^2 at 75Pa (0.2 L/sm^2) had over 30% heat recovery rate on the air flows in Baltimore (BAL in Figure 5 left).

6 Moisture Performance

The layer in the wall that would accumulate moisture during the winter months when air leaks are present would be the oriented strand board (OSB). OSB is the first low permeance material that is air tight as a material but that can leak air if the contact surfaces between the OSB and the framing are not sealed. Figure 6 shows the average amount of moisture in the OSB layer in the simulated wall as a function of time for walls with three different air leakage characteristics: 0.01, 0.02 and 0.04 cfm/sqft at 75Pa. The effect of the different air leakage rates is minimal on the overall moisture content of the OSB and in all the cases the initial moisture content representing 80% relative humidity is higher than the second year moisture content at any time.

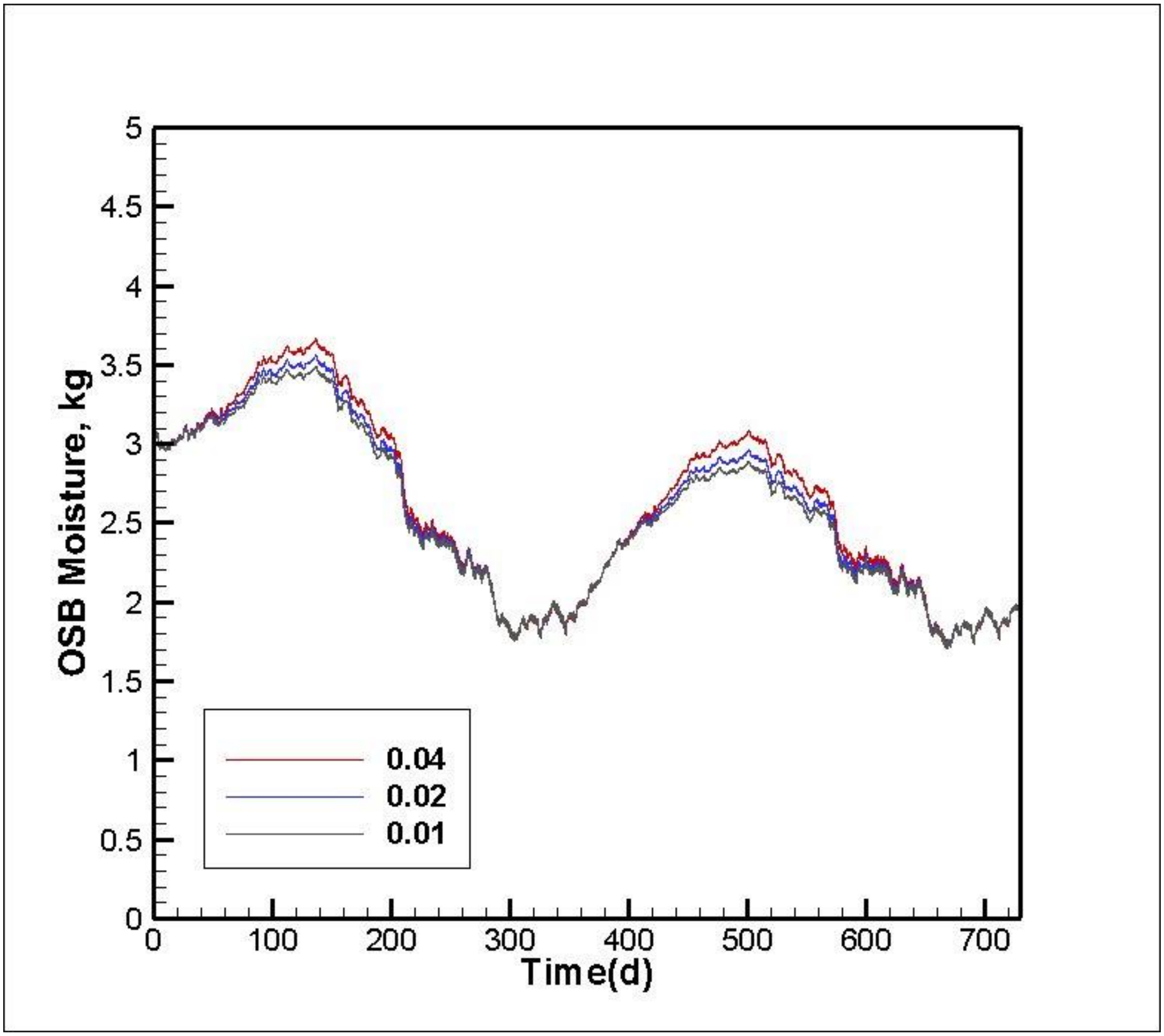

Figure 6. Average OSB moisture (kg) in the wall as a function of air leakage (cfm/sqft at 75Pa) in Baltimore, MD.

Mold growth predictions were carried out using the Mold Index method by Viitanen (1999) for wood based materials. The maximum mold index present in the wall during the simulated year is shown in Figure 7. The maximum mold index is 5.1 for the lowest airflow rate for a single small point of air entry in the area of the band joist. The maximum mold index in the wall area not including the rim/band joists was <3.9. This indicates that the air leakage paths around band/rim joists need to be carefully sealed.

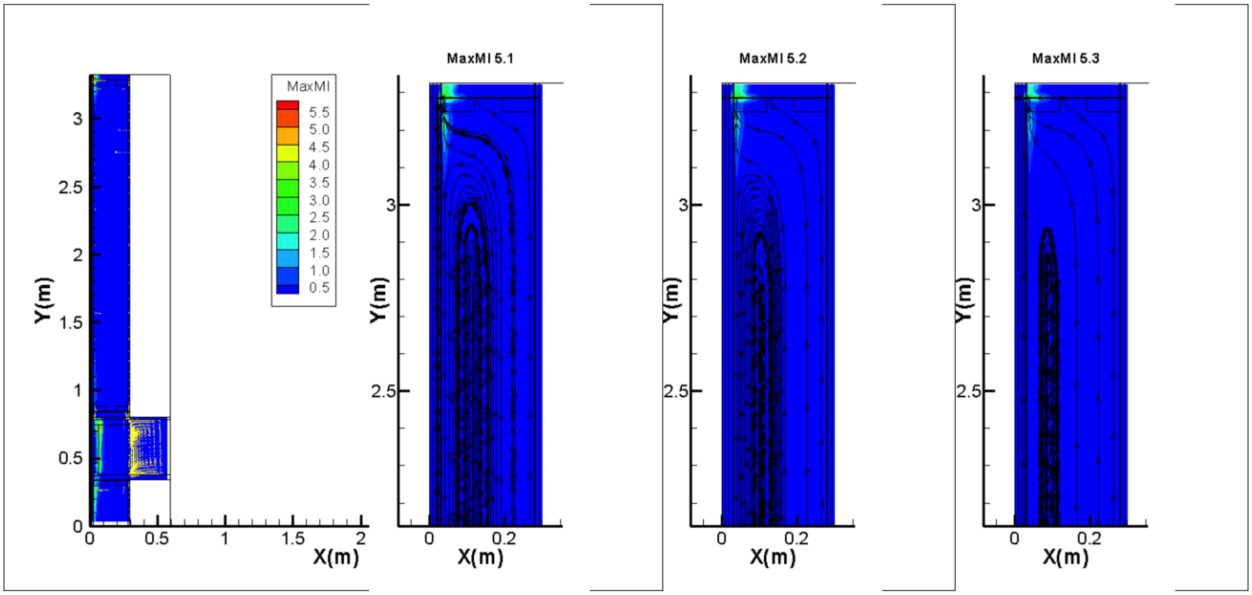

Figure 7. Predicted Mold Index at air tightness ratings 0.01, 0.02 and 0.04 cfm/sqft (left to right). Whole assembly for maximum mold index. Baltimore, MD. Streamlines show air movements through the wall cavity.

7 Conclusions

Results show that heat recovery is present in the dynamic analysis of heat and moisture transport in double studded wall systems. The impact of air flows on the total heat loss through the walls (including air leakage and conduction) is less than 15% in walls with less than 0.04 cfm/sqft air leakage at 75Pa. 0.04 cfm/sqft at 75Pa translates to approximately a building air leakage of 0.3-0.4 ACH50 (wall and roof contribution only, assuming flow exponent n=0.7). In addition the moisture analyses show that these air leakage rates don't play a major role in moisture induced problems in these walls.

These results show no need for the air leakage requirement to be any lower than the current requirements for air tight wall assemblies (0.04 cfm/sqft at 75Pa).

8 References

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9 Appendix A: Results per location

The boundary conditions (temperature and relative humidity) of the outdoor and indoor conditions are shown first following with the exterior sheathing moisture as a function of air leakage. Then the mold index contours are presented for walls with different air leakage rating (0.01, 0.02 or 0.04 cfm/sqft at 75Pa).

Overall the results indicate that the airflow rates at these low flow rates have little impact on the wall moisture as well as the mold index. Very isolated small areas (exit point of air) show high predicted mold index when calculated for very sensitive materials (wood). The mold index values should be considered as directional only.

9.1 Houston, TX

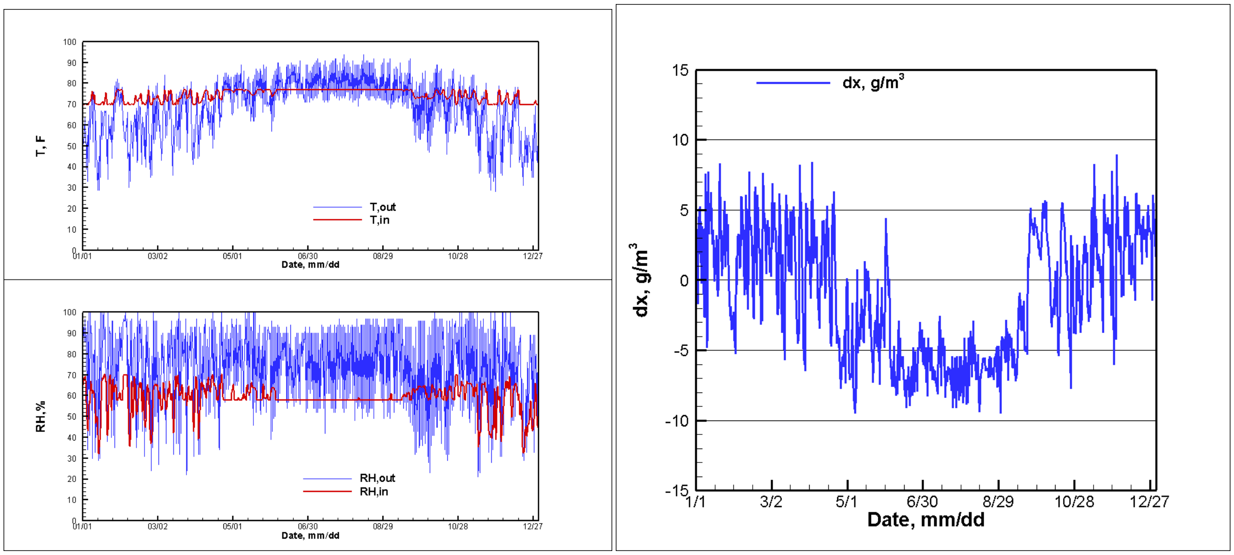

Figure 8. Outdoor and Indoor temperature and relative humidity (left) and moisture load (right) in Houston, TX.

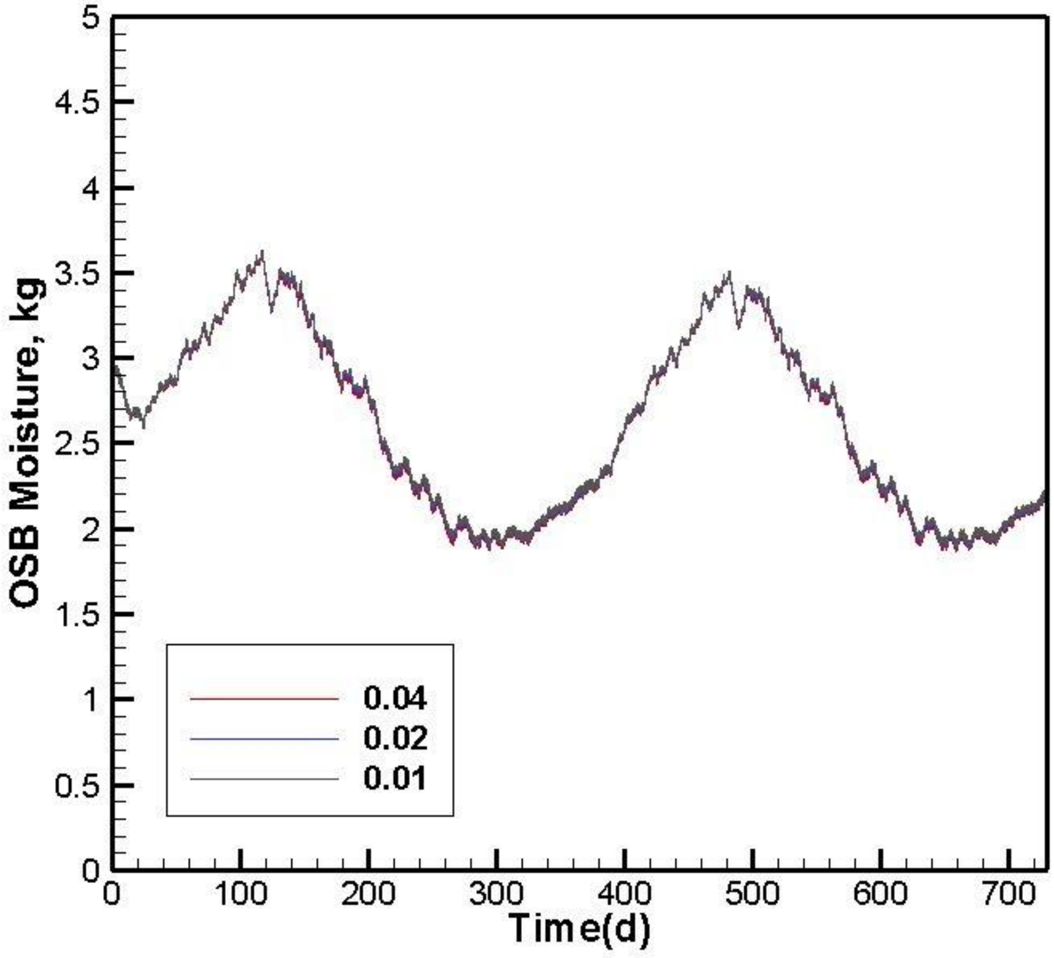

Figure 9. Average OSB moisture (kg) in the wall as a function of air leakage in Houston, TX.

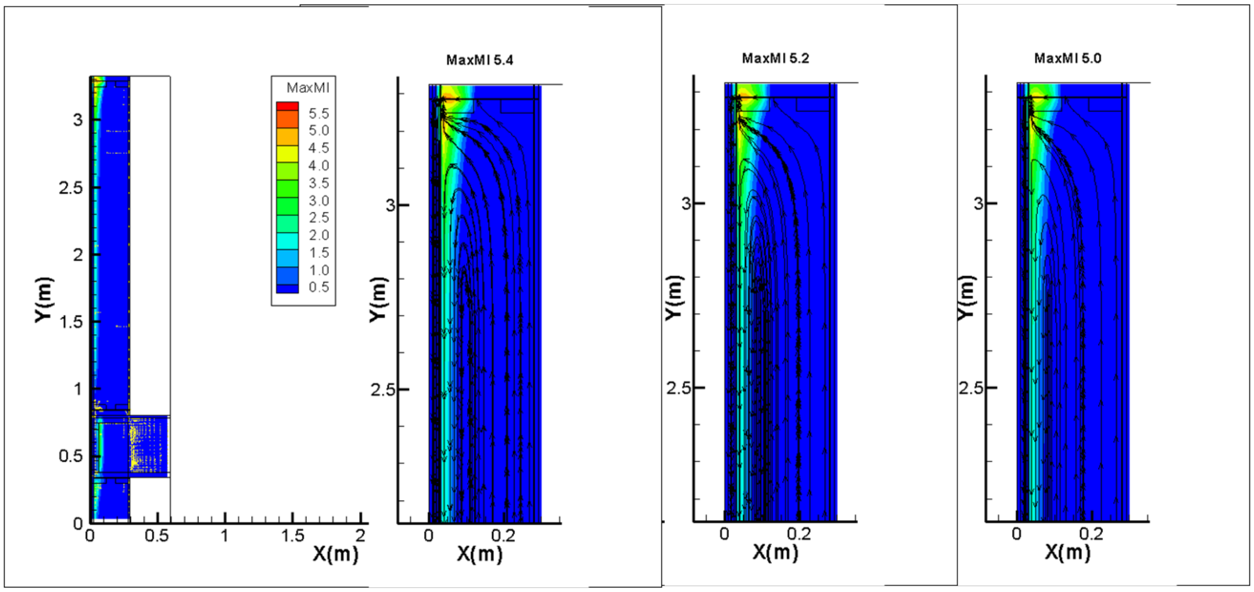

Figure 10. Predicted Mold Index at air tightness ratings 0.01, 0.02 and 0.04 cfm/sqft (left to right). Whole assembly for maximum mold index. Houston, TX.

9.2 Atlanta, GA

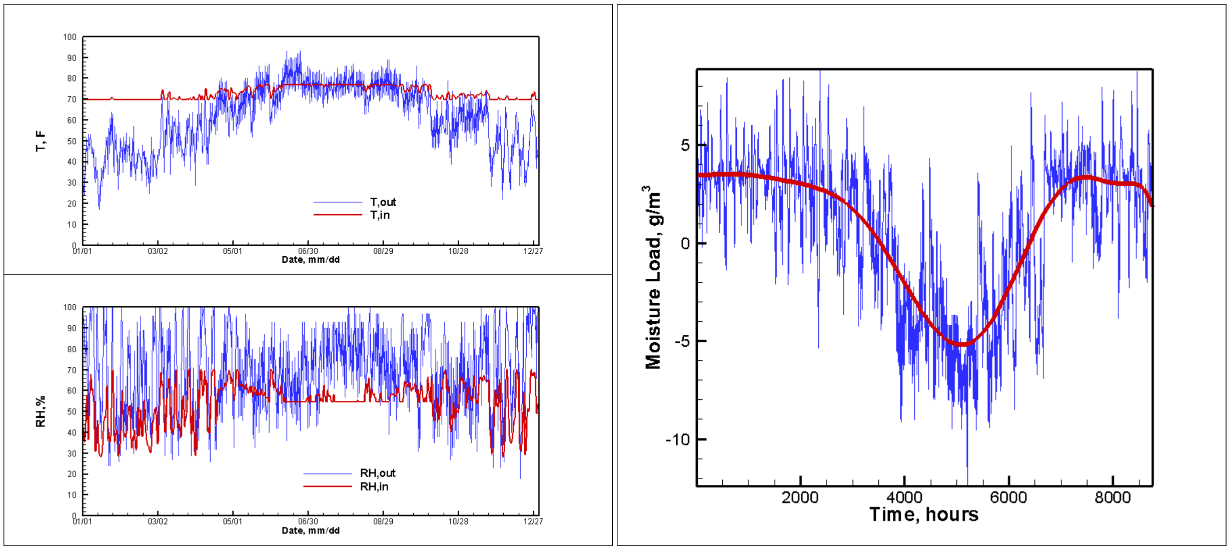

Figure 11. Outdoor and Indoor temperature and relative humidity (left) and moisture load (right) in Atlanta, GA.

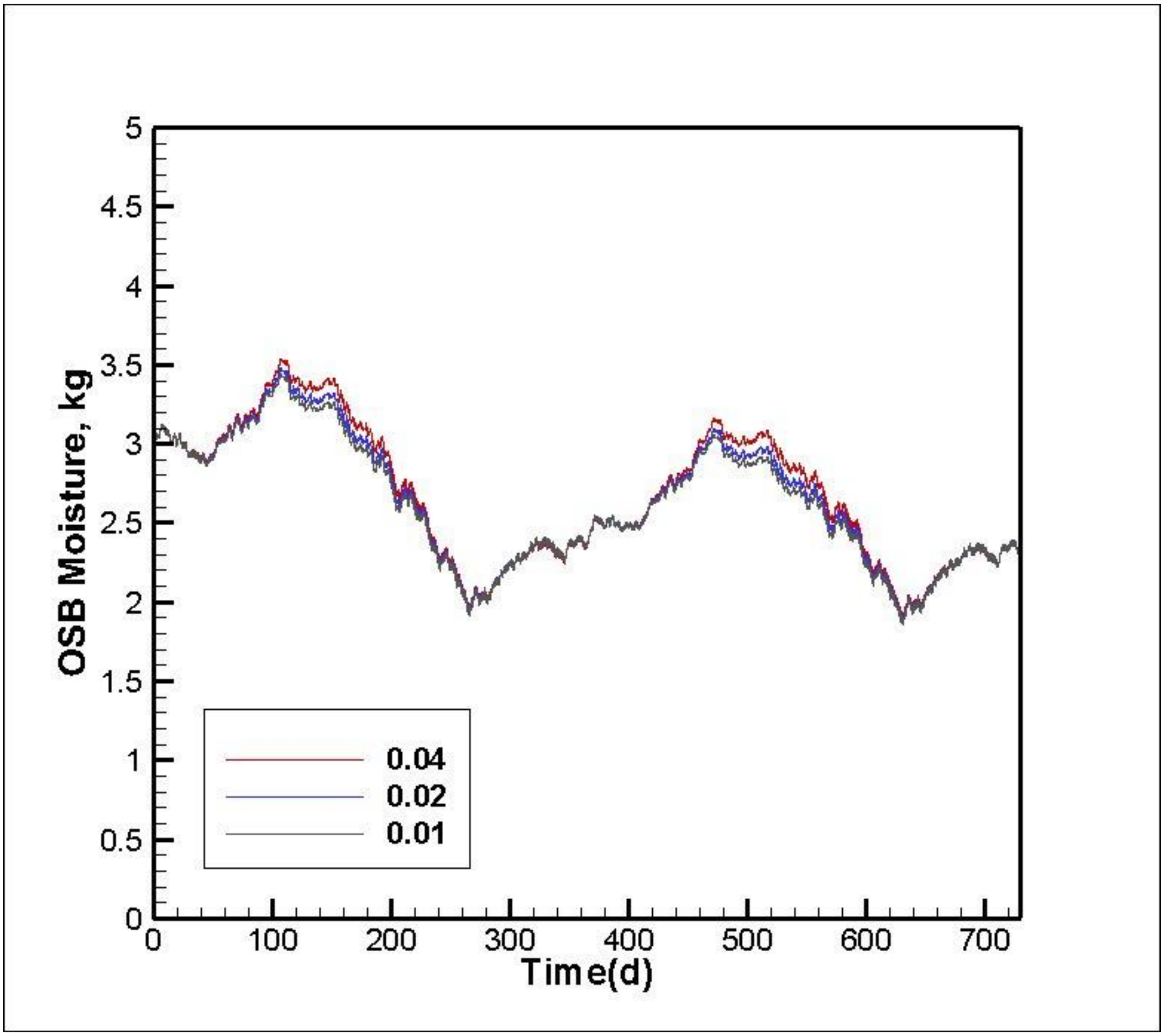

Figure 12. Average OSB moisture (kg) in the wall as a function of air leakage in Atlanta, GA.

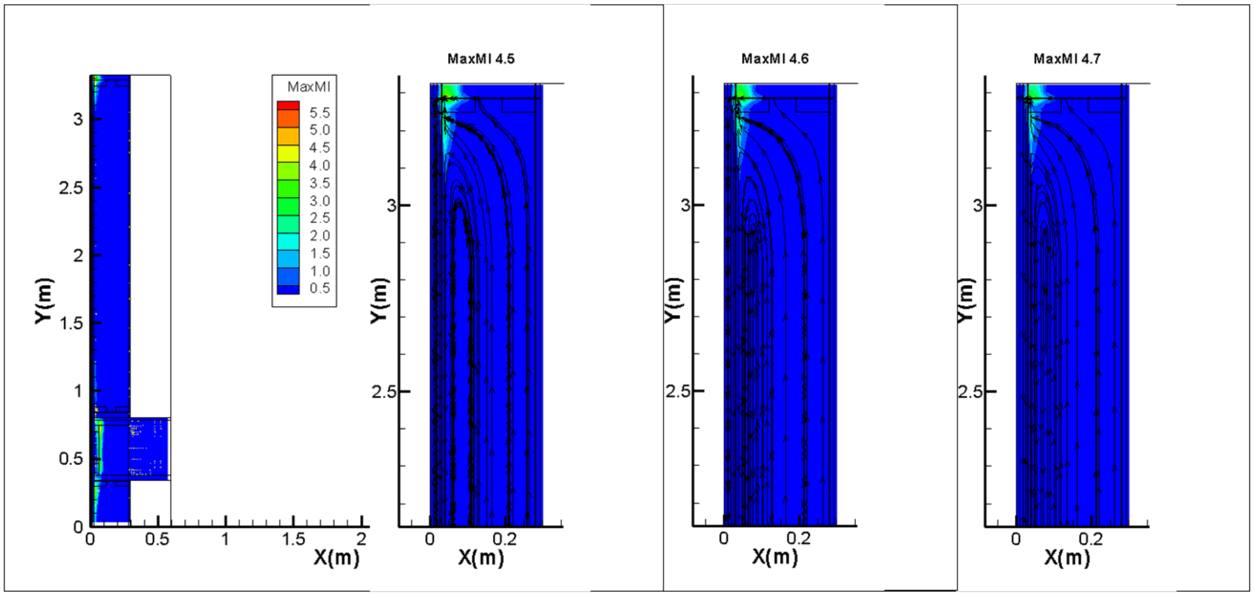

Figure 13. Predicted Mold Index at air tightness ratings 0.01, 0.02 and 0.04 cfm/sqft (left to right). Whole assembly for maximum mold index. Atlanta, GA.

9.3 Seattle, WA

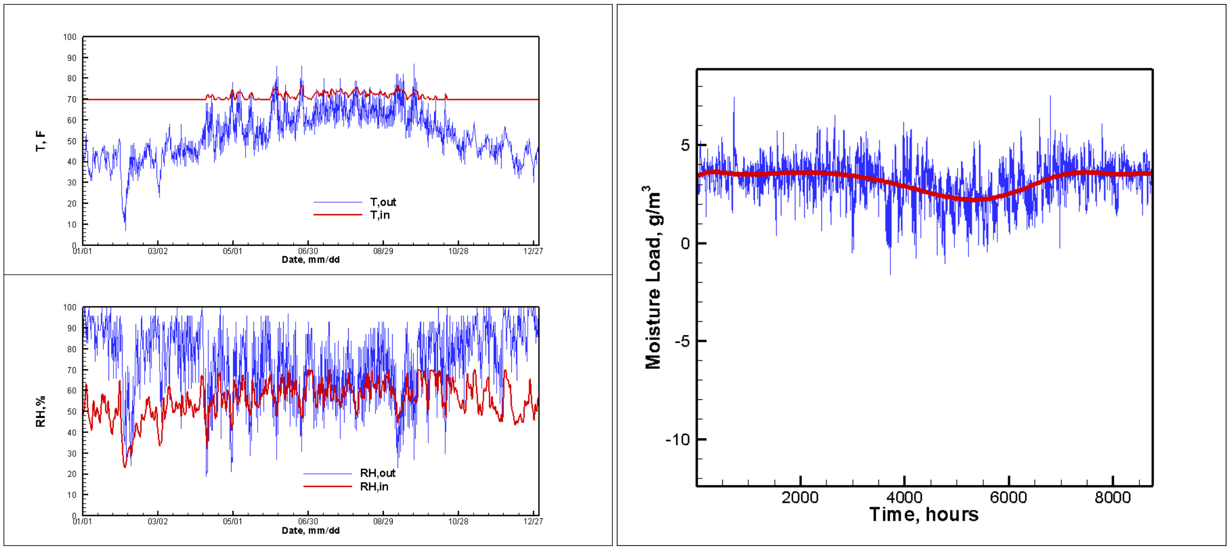

Figure 14. Outdoor and Indoor temperature and relative humidity (left) and moisture load (right) in Seattle,WA.

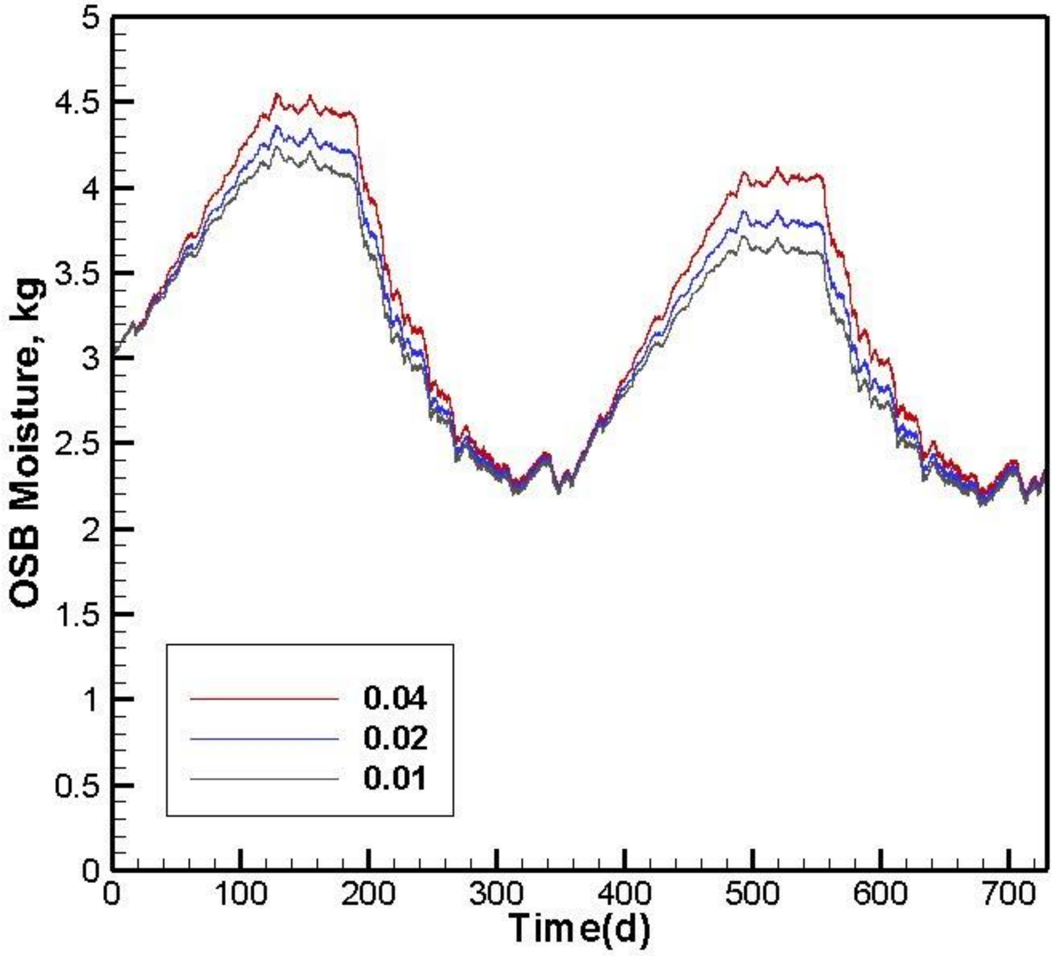

Figure 15. Average OSB moisture (kg) in the wall as a function of air leakage in Seattle, WA.

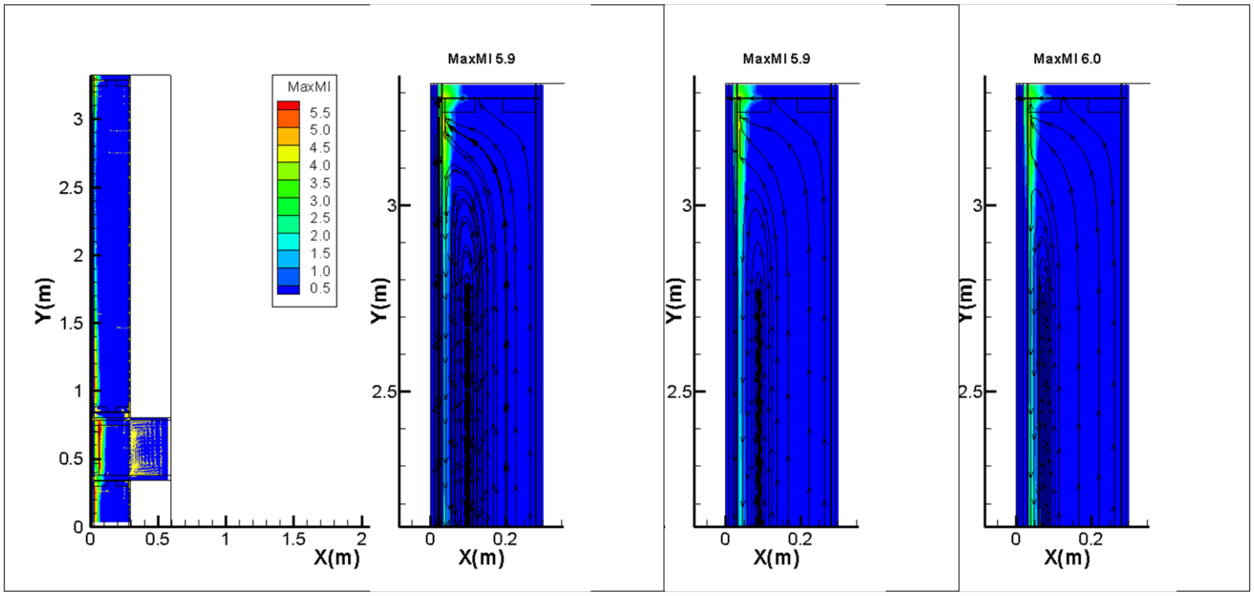

Figure 16. Predicted Mold Index at air tightness ratings 0.01, 0.02 and 0.04 cfm/sqft (left to right). Whole assembly for maximum mold index. Seattle, WA.

9.4 Baltimore, MD

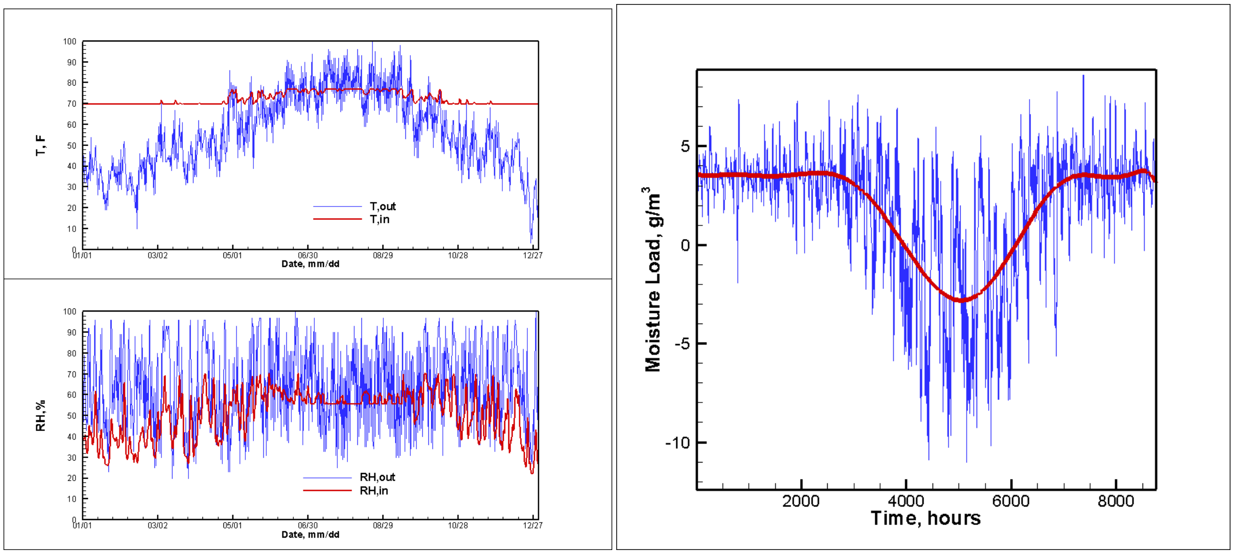

Figure 17. Outdoor and Indoor temperature and relative humidity (left) and moisture load (right) in Baltimore, MD.

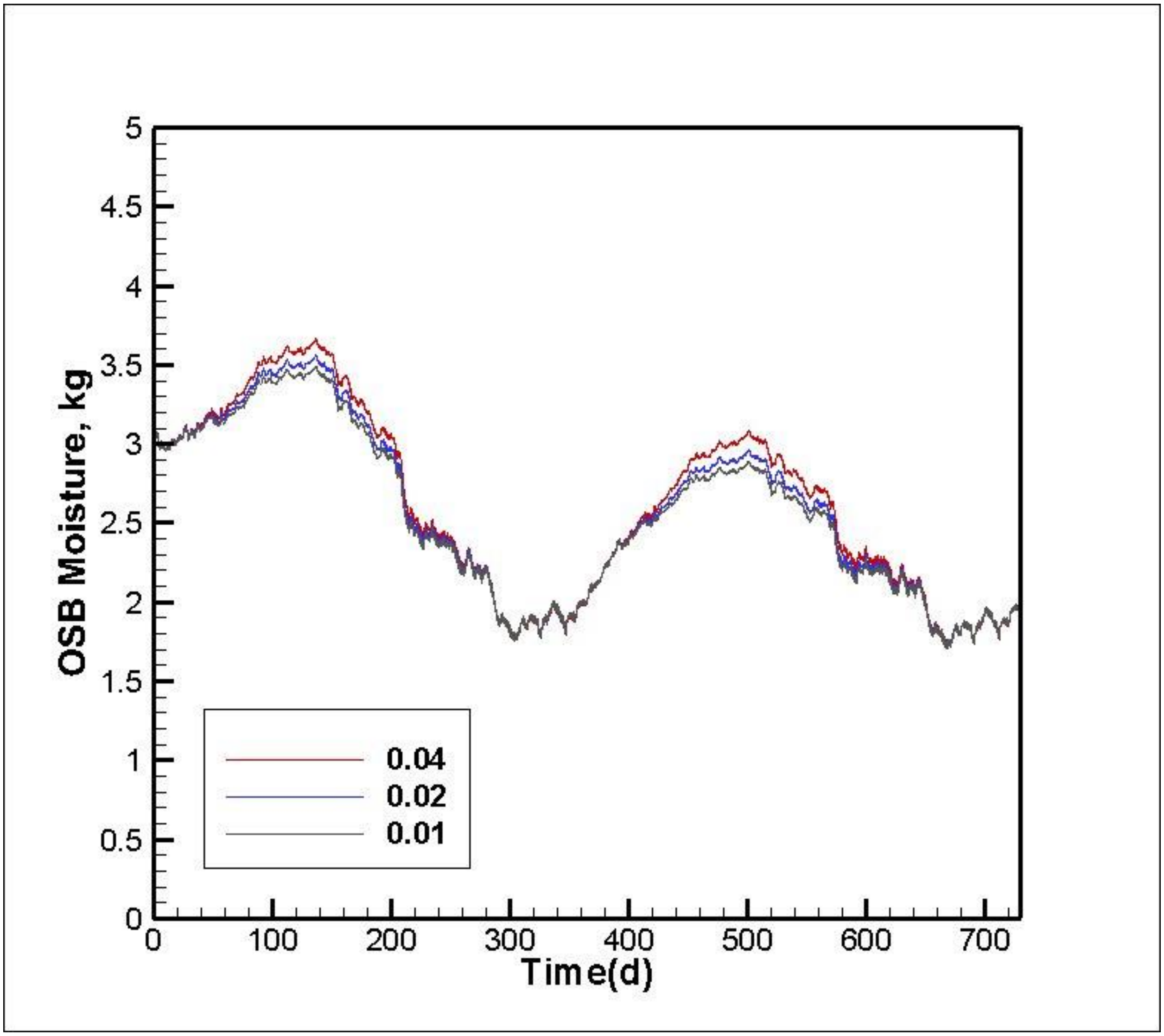

Figure 18. Average OSB moisture (kg) in the wall as a function of air leakage in Baltimore, MD.

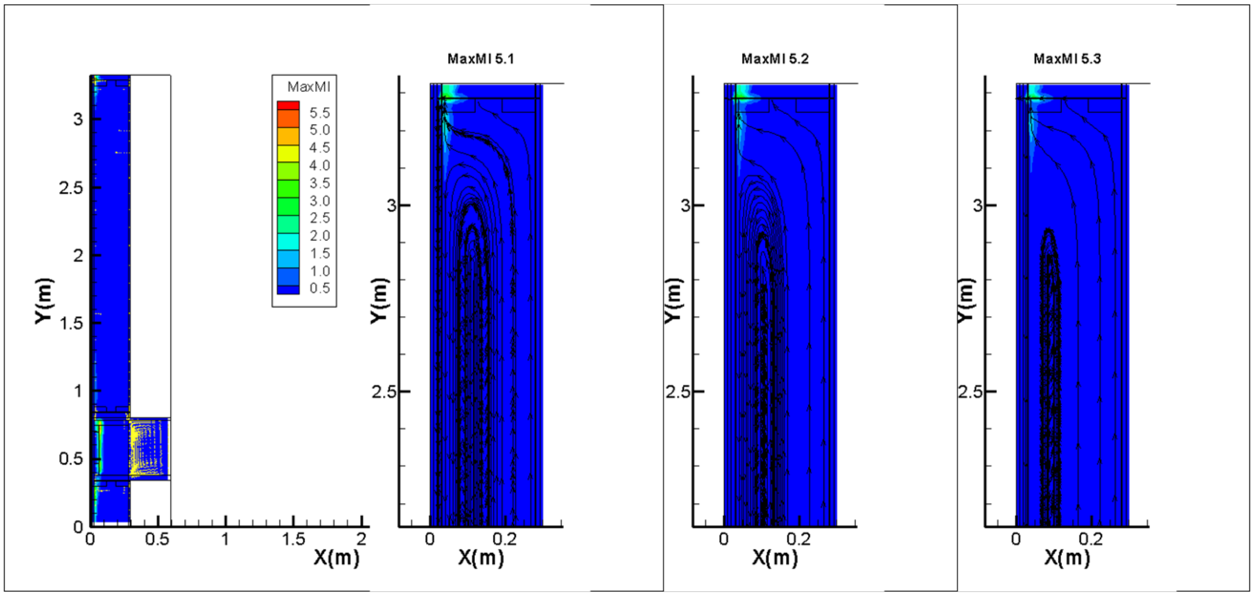

Figure 19. Predicted Mold Index at air tightness ratings 0.01, 0.02 and 0.04 cfm/sqft (left to right). Whole assembly for maximum mold index. Baltimore, MD.

9.5 Boston, MA

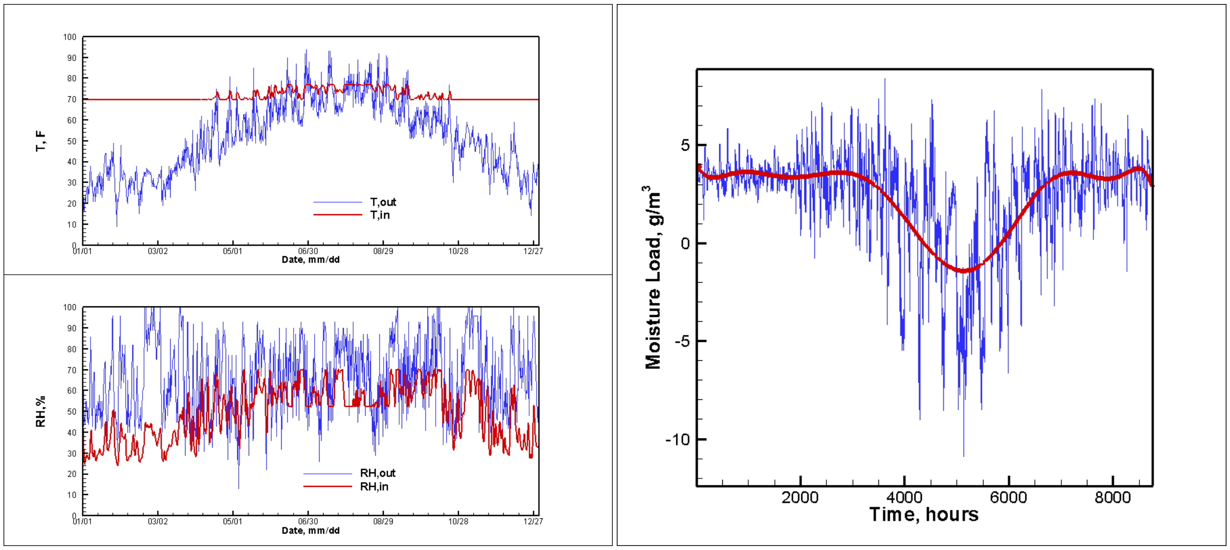

Figure 20. Outdoor and Indoor temperature and relative humidity (left) and moisture load (right) in Boston, MA.

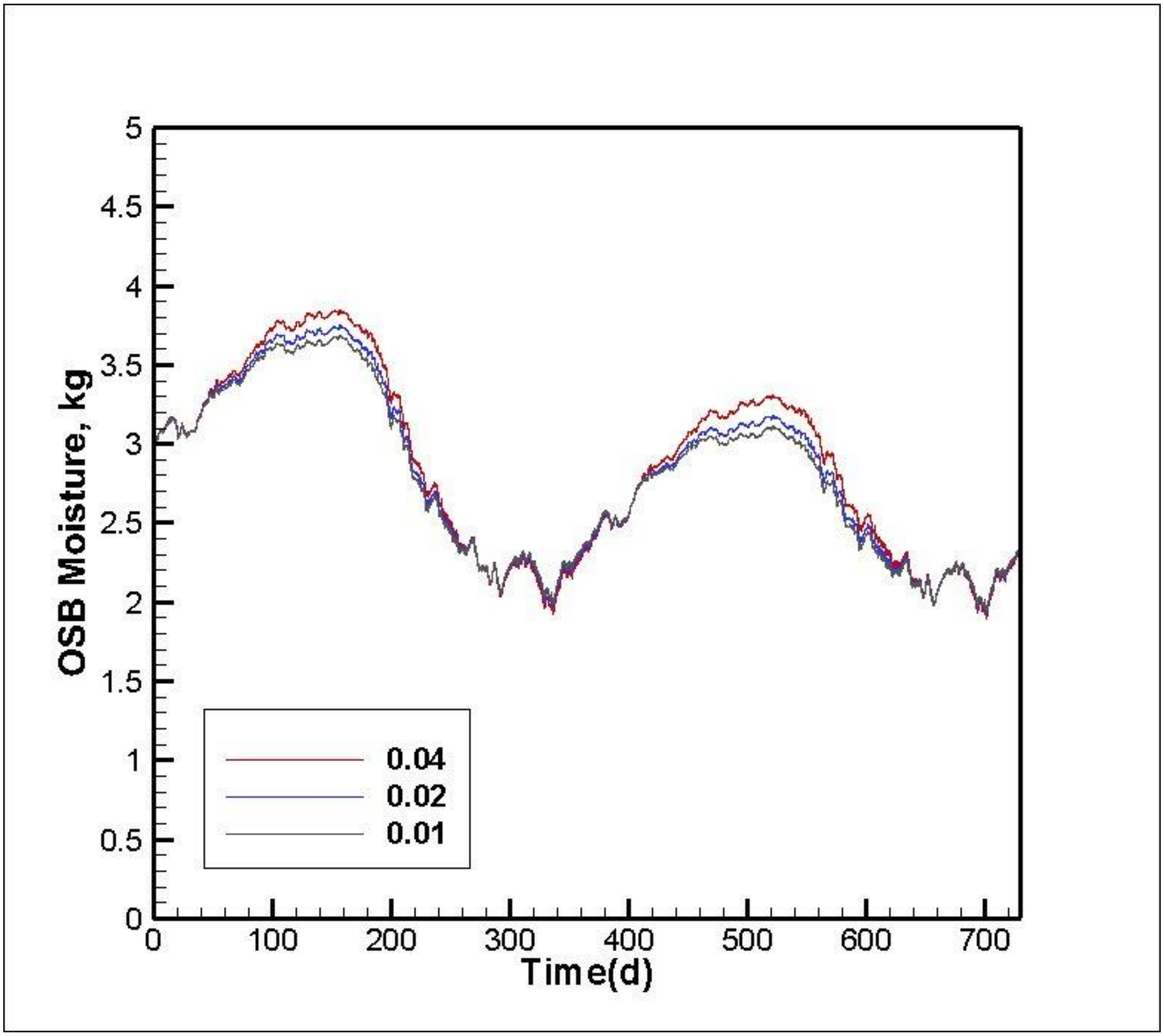

Figure 21. Average OSB moisture (kg) in the wall as a function of air leakage in Boston, MA.

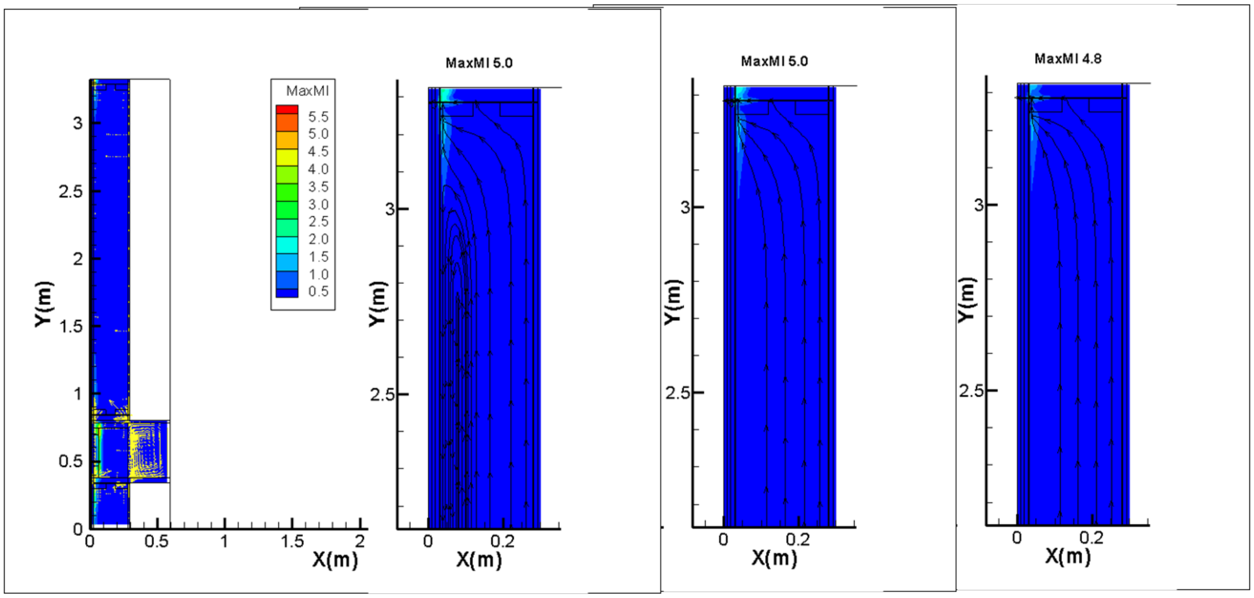

Figure 22. Predicted Mold Index at air tightness ratings 0.01, 0.02 and 0.04 cfm/sqft (left to right). Whole assembly for maximum mold index. Boston, MA.

9.6 Fairbanks, AK

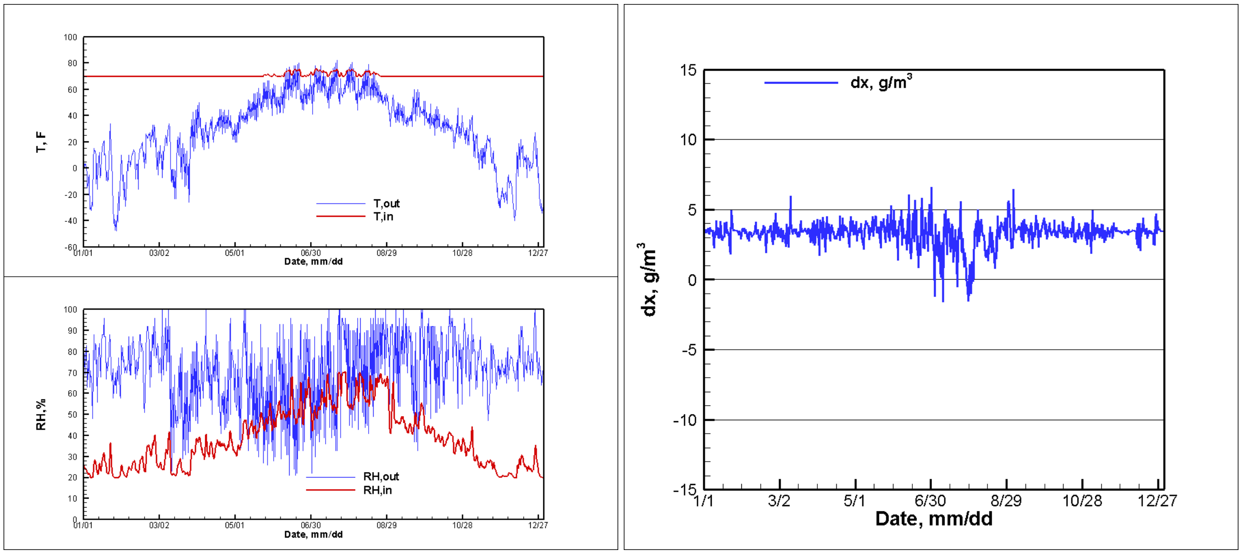

Figure 23. Outdoor and Indoor temperature and relative humidity (left) and moisture load (right) in Fairbanks, AK.

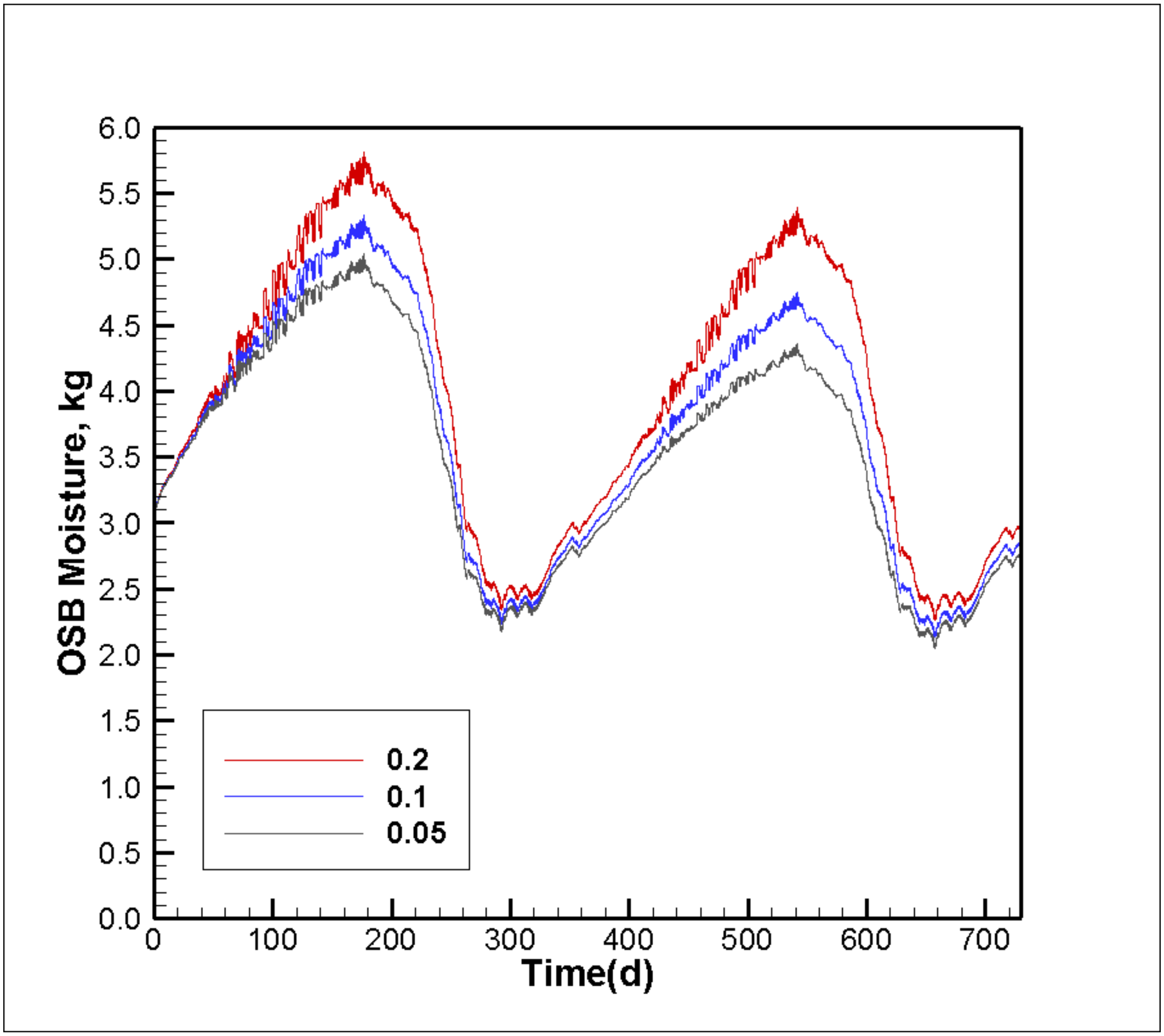

Figure 24. Average OSB moisture (kg) in the wall as a function of air leakage in Fairbanks, AK.

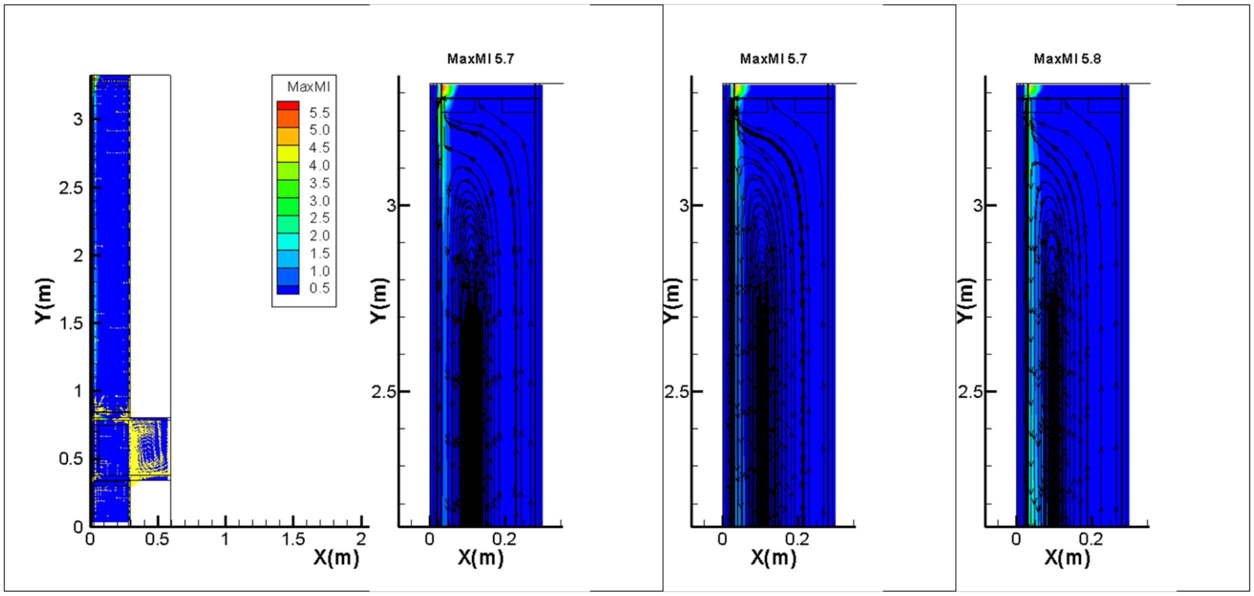

Figure 25. Predicted Mold Index at air tightness ratings 0.01, 0.02 and 0.04 cfm/sqft (left to right). Whole assembly for maximum mold index. Fairbanks, AK.

9.7 Minneapolis, MN

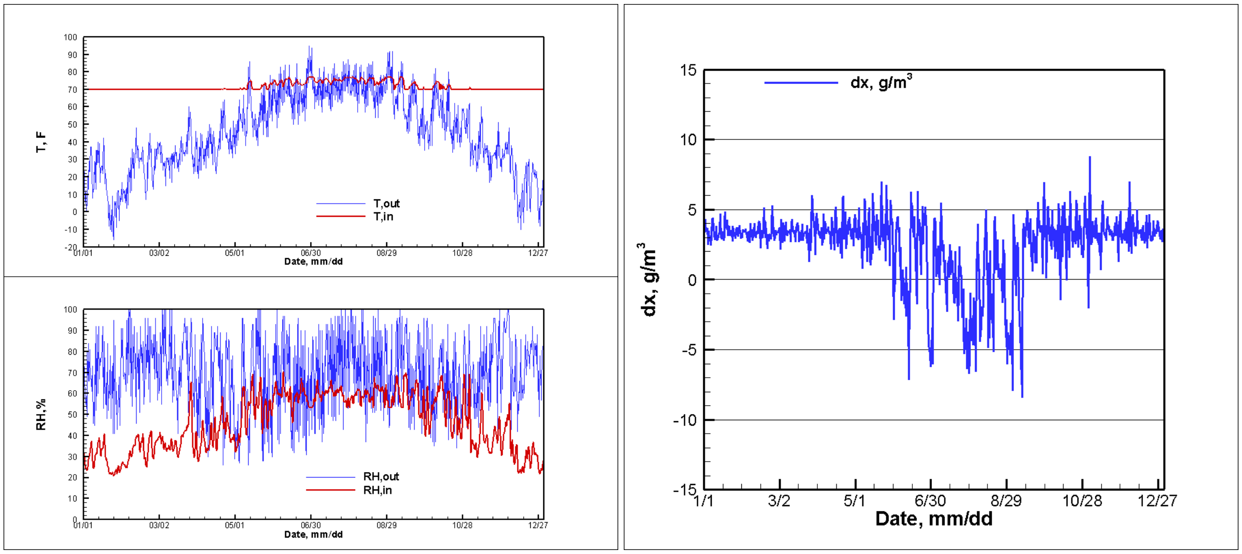

Figure 26. Outdoor and Indoor temperature and relative humidity (left) and moisture load (right) in Minneapolis, MN.

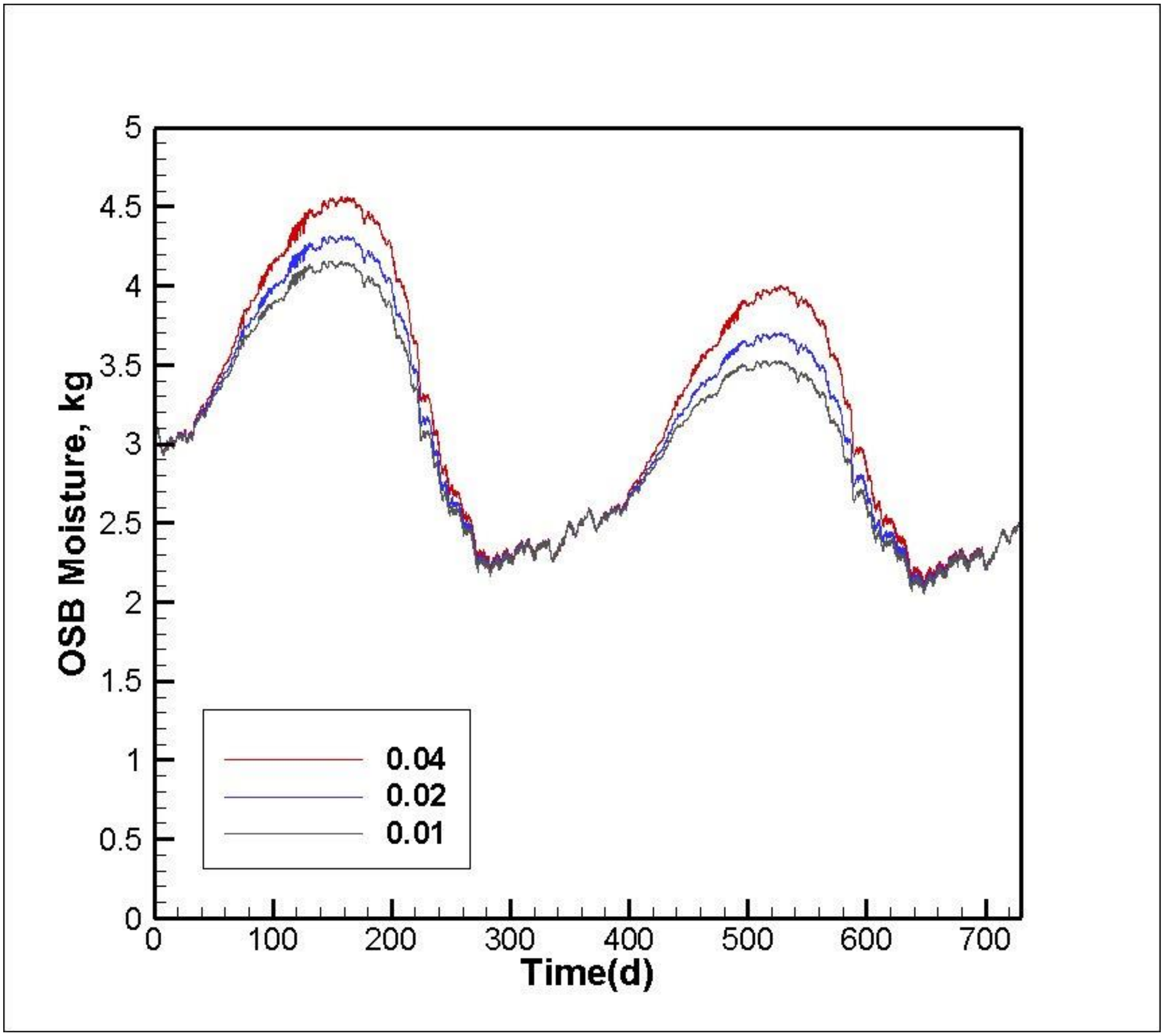

Figure 27. Average OSB moisture (kg) in the wall as a function of air leakage in Minneapolis, MN.

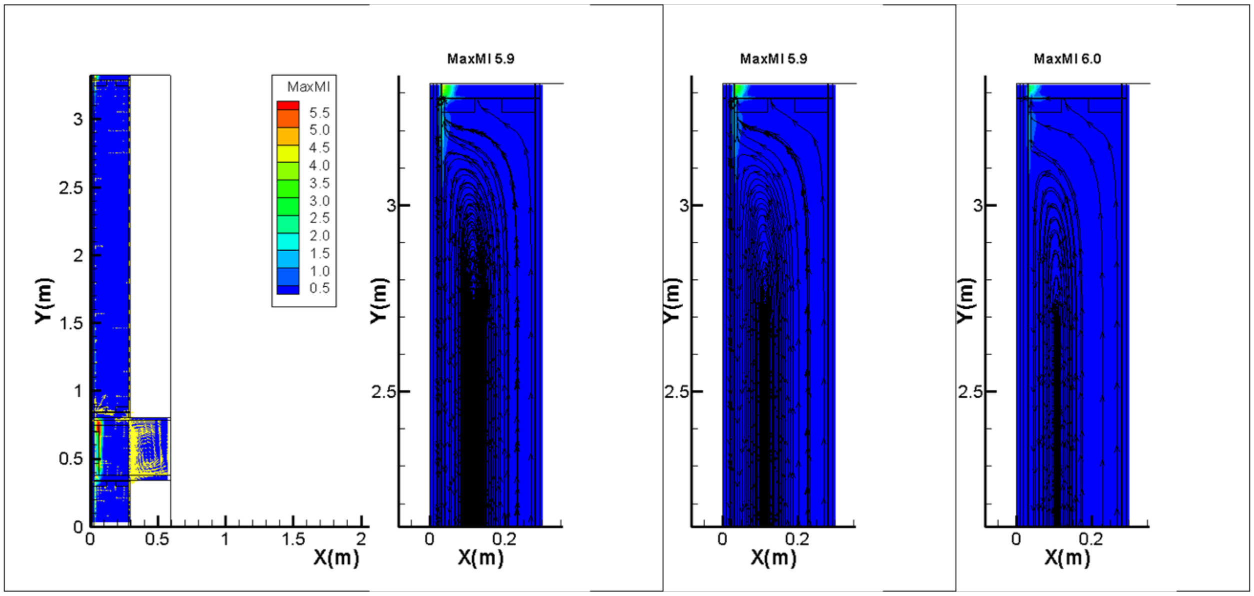

Figure 28. Predicted Mold Index at air tightness ratings 0.01, 0.02 and 0.04 cfm/sqft (left to right). Whole assembly for maximum mold index. Minneapolis, MN.

10 Appendix B – Assembly air leakage versus whole-building

As noted in section 1, there are more air-leakage paths for a building overall than for an air-barrier assembly. The assembly simulated in this study has five leakage paths (see Figure 3.) Figure 30 below illustrates some others.

Some indication of the relation between assembly air leakage and whole-building air leakage can be gleaned from Wolf & Tyler (2013). That study sought to characterize the severity of various kinds of leakage paths in detail, with a view toward prioritizing air-sealing work. Thirteen kinds of linear joints and a few kinds of point opening leaks were studied using full-scale laboratory mockups and/or by step-by-step air-sealing of an actual vintage-1977 house (freshly resheathed). Each leakage path was characterized with a flow coefficient and exponent. This detailed cfm50/foot data was used to make projections of the contributions of each leakage path to ACH50 for a one-story and two-story house design, thereby taking into account both the leakiness per foot or per instance and the length of the joints or number of penetrations.

There are some drawbacks to using this data to infer a relation between assembly air leakage and whole building:

- The data mostly pertains to a building that is not intentionally being air-sealed. The relative importance of the different leakage paths could be different in the case where a continuous air barrier is being designed and executed. (The authors did note that leakage via paths connecting through the wall cavity was greatly reduced, if the bottom of the drywall happened to be caulked to the floor for aesthetic reasons, but that this could not be relied on because it would only be done for some types of floor coverings.)
- The study omitted some whole-building leakage paths, such as door thresholds, operable windows, and dryer vent dampers. Such leakage paths exact an energy penalty, but could be considered “nonthreatening” with regard to moisture damage in the assemblies.

Nonetheless, some indication can be obtained as follows:

Though the assemblies were not exactly the same, the ones present in the simulated assembly used here could be considered to be of these types, by the terminology of Wolf & Tyler (2013):

- Top plate-to-attic
- Band joist
- Sheathing-to-plate (top only here)
- Between exterior top plates
- Bottom plate to subfloor

The earlier study also included, in addition to both top and bottom of the sheathing:

- Recessed lights
- Duct boots
- Garage-house common wall
- Corners (interior pointing)
- Corners (exterior pointing)

- Window/door framing-to-sheathing
- Vertical sheathing joints
- Sill plate-to-foundation

For each of these, Wolf and Tyler gave a low-to-high range, for the contribution to whole-house leakage, in ACH50. Assuming a uniform distribution for each and constructing a 1000-point Monte Carlo gives 2.5 +/- 0.4 ACH50 for the full set of leakage paths and 1.5 +/- 0.4 ACH50 for the subset of paths included in the present study. This represents a reduction factor from whole-house to assembly of 0.61.

If some additional allowance for windows is added to the whole-house leakage, the reduction factor drops a bit further. In the North American Fenestration Standard, the acceptance level for most product types is 0.3 cfm75/ft2. On a per square foot basis this is much higher than the ABAA's air barrier criterion of 0.04 cfm75/ft2, but windows might only be 15% of the wall area and less of the total envelope. Assuming for Wolf & Tyler's model buildings: a length/width ratio of 1.6, windows at 15% of the wall area, and a flow exponent of 0.8 for the windows, such that a window rated 0.3 cfm75/ft2 leaks 0.22 cfm50/ft2, then there would be an additional 0.09 to 0.15 ACH50 added to the 2.5, bringing the reduction factor to 0.56 for the assembly relative to the building.

Therefore, though there are some uncertainties and limitations, a whole-building criterion might reasonably be set at 0.08 cfm75/ft2. Anecdotally, operable windows are believed to leak more in the field than the laboratory ratings would indicate, which would put such a criterion on the safe side for the assemblies.

In Kunzel et al (2012), a distinction is made between energy air leaks and moisture air leaks. "Energy air leaks" take rather direct paths, and are less-threatening from a moisture point of view because the air carries enough heat to warm up the channel, preventing condensation. In "moisture air leaks", the air takes more narrow and torturous paths, giving it time to cool down and condense on the cold side of the assembly. There is some indirect evidence that what tends to happen in the process of air-sealing is that the more direct energy leaks get sealed preferentially - that moisture air leaks may represent only about 10% of the total air leakage in standard construction, but might be 70% of the leakage in airtight construction: They cite experimental results on the amount of condensation due to air convection, occurring in lightweight airtight constructions with vapor retarders, and back-calculated an "air permeance" of 0.007 m3/(m2.h.Pa) or 0.029 cfm75/ft2 (assuming laminar flow - a flow exponent of 1). They then compare this with the airtightness assumptions for airtight construction and standard construction in ASHRAE 160, which they convert as 0.01 and 0.06 m3/(m2.h.Pa) respectively, or 0.041 and 0.25 cfm75/ft2.

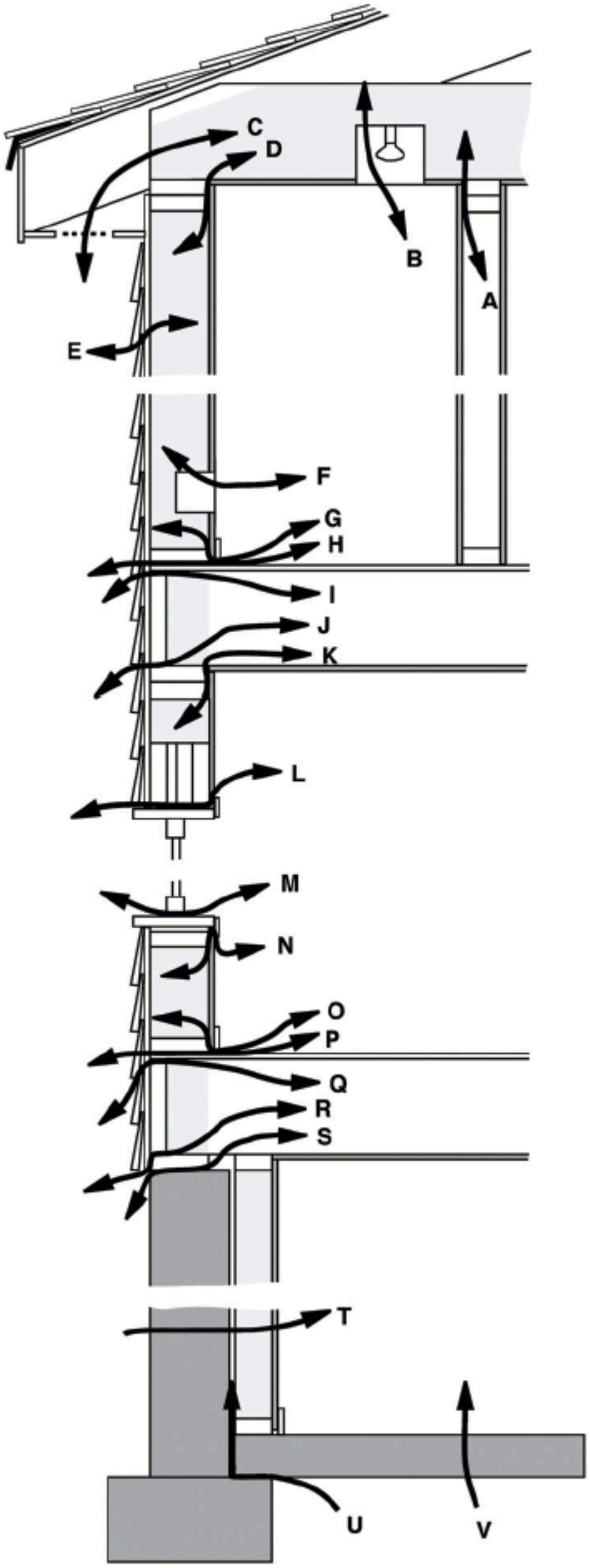

Figure 30. Schematic of a house cross section showing the various air leakage paths. From Wolf & Tyler (2013).