Experiential Learning Exercises to Further Understanding of Complex Building Science Principles

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ABSTRACT

In high-performing building enclosures, the reduction of heat losses can lead to higher accumulations of moisture from condensation and vapor diffusion phenomena, which in turn can lead to rot, corrosion, mold, and overall deterioration of buildings. Building construction professionals have the unique opportunity to catch design and construction errors, which if unattended will lead to costly repairs down the road. New materials, frequent change orders on site, or process changes can have a lasting and expensive impact on functionality and durability of enclosure systems. A sound understanding and proficiency in building physics and its multifaceted principles can provide students with competencies to construct and promote better performing buildings in regards to durability, efficiency, health, and comfort. Teaching efforts in this area need to move beyond traditional pedagogical practices of transferring knowledge to a more stimulating and interactive approach, where educators facilitate environments for learners to gain knowledge through interactions with building components, performing independent experiments, problem-solving, and reporting on the findings gained in the process. This paper discusses the context, design, and implementation of several building physics education lab exercises, in which interstitial and other condensation phenomena in exterior wall assemblies can be evaluated. The lab activities engage students utilizing an experimental setup of a mobile cold climate chamber, a mix of exterior wall materials, and multiple temperature and humidity sensors, to investigate the occurrence and prevention of interstitial condensation. By observing and physically touching ice that builds up within the cavity on sheathing, or fiber insulation soaked with condensate, instructors can deliver a powerful educational message even within the constraints of a classroom through this approach.

BACKGROUND AND MOTIVATION

Building enclosures date back to the first societies seeking shelter from the environment. As suitable materials were explored to provide shelter, the first construction techniques emerged. Over centuries, new materials and construction processes have evolved and sometimes been forgotten again, just to be reinvented many decades later. The history of building enclosure systems is full of anecdotes where known principles were forgotten or ignored in favor of architectural expression and exploration of new materials (Straube 2006). At times, it feels we once again forget to teach building physics principles to our A/E/C students, an observation derived from the absence of related learning objectives in accreditation requirements for university programs in the U.S. Architectural engineering has come a long way – the first architectural engineering course of study was offered at the University of Illinois (now the University of Illinois at Urbana-Champaign) back in 1890 (Uihlein 2016). Architectural engineering has since been developed as a specialization of architectural education, with some programs even offering a special focus on residential construction (Memari et al. 2014). However, teaching building science principles can be challenging and different approaches from virtual environments (Hatherly 2017; Setareh Mehdi et al. 2005) to hands-on activities (Denzer and Heimbuck 2011) have been explored to teach structural, thermal, lighting, and broader energy performance principles.

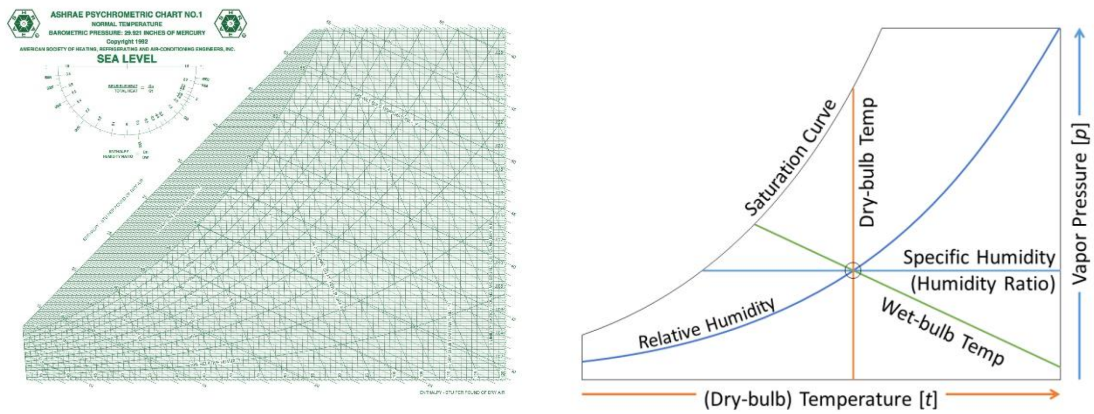
There are also efforts of broader integration of life-cycle considerations with new materials and systems and their service life performance expectations utilizing quantitative methods and test protocols incorporated into an assessment framework (Mora et al. 2011). Nevertheless, in terms of control strategies in building enclosures, the control of moisture pathways is still the most critical one when it comes to damage functions, which can range from direct water leakage to condensation and capillary movement. The result are damage states such as rot, mold, spalling, or corrosion to name only the most common manifestations. Still, this specific area of building physics or building science is significantly under-represented in curricula of higher education. The problem sets that come together in moisture control are by no means new (Rose 1997), though they require broader attention with emerging high-performance building materials and assemblies, where the reduced heat flow now deprives the enclosure system of its “self-healing” mechanism, namely the transport of interstitial moisture in form of vapor along with thermal transmission losses.

To make the complex principles of moisture migration and control more applicable, a series of experiments have been devised, which gradually bring students closer to the different problem sets that are found in building enclosures. The series sets out in exploring psychrometric properties in daily life, then moving on to understand the conditions required for the “perfect storm” observed as condensation within enclosure systems, to the ultimate frontier of building physics – the strange world of vapor pressure and diffusion through layers of different materials.

PHASE 1: EXPLORING PSYCHROMETRICS

Psychrometrics, a field that describes the physical and thermodynamic properties of gas-vapor mixtures – in the context of building enclosures, air and water vapor – can be overwhelming and confusing for those who do not have a background in mechanical engineering. It may be the multitude of properties depicted in psychrometric charts, or the sheer density of curves, lines, and different scales that makes these charts so intimidating (Figure 1a).

To break these properties into more tangible elements educators simplify the schematic diagrams, e.g. depicting only the core elements used in building physics for further discussion as shown in Figure 1b.



a) **b)**

Figure 1. Psychrometric charts (a) as published by ASHRAE and (b) schematic chart for educational reference

Among these properties, the dry-bulb (DB) temperature, which refers to the commonly measured air temperatures, are the most relatable metric and share a broad understanding of how values can be obtained. Relative humidity (RH) is also commonly used in communications such as weather forecasts. However, when pressed on how RH can be measured, most people outside the HVAC profession will draw a blank. Then again, a closer look at the psychrometric chart also reveals a second type of temperature, the so-called wet bulb (WB) temperature that intersects with DB temperatures, and probably can be obtained with a thermometer as well. However, the concept and measurement of WB temperatures is more complex. It requires a thorough understanding of the physics occurring during evaporation processes and how those relate to temperature measurements.

To provide a stimulating setting for students for exploring this relationship, an in-class experiment has been developed that engages them by applying theory to practice. This first experiment is also designed as an icebreaker to foster team thinking and exchange of ideas while observing others in the same situation.

After explaining the energy exchange between media during the endothermic process of evaporation[1], the student teams are exposed to a "MacGyver"[2] setting, where they have to quickly determine the relative humidity in the room (in which they are trapped)

[1] e.g. Michael Ermann provides an excellent illustrated version for explaining this phenomenon for architects when discussing "How Air Conditioning Works – Part 1" https://youtu.be/2wZb6HgIDE0
[2] MacGyver is an action-adventure series that ran in the U.S. and abroad in the later eighties. MacGyver employs his resourcefulness and his knowledge of chemistry, physics, and technology to create inventions from simple items solving problems in situations that are often life-or-death crises. https://en.wikipedia.org/wiki/MacGyver

in order to safely disarm a bomb that otherwise could go off. As typical for the MacGyver series, there are always a set of items “conveniently” found nearby to solve the problem.

Materials, Equipment, and Preparation

Each student team (teams of 3-5 work best) is provided with the following items that they “found” in the space: a semi-broken thermometer; a few rubber bands; a piece of string; some gauze pads from an emergency kit; and a paper clip[3] (Figure 2)

Figure 2. Items to be provided for “MacGyver” experiments

The thermometers can be purchased from your local hardware store and have no need to be highly accurate as they will be only used for comparative temperature measurements, where they should function accurately enough. A couple of rubber bands are sufficient, but a few extra may not hurt in case a band rips or gets lost in the process. In terms of string, 2-3 feet is enough and can be pre-cut for the students to use without the need for handing out knifes or scissors. Gauze pads can be purchased in bulk at local pharmacies, and 3-4 pads are sufficient for each team to have.

Experiment Setup

The setup for these experiments is minimal once the items are purchased, prepared, and sorted for each team. It has been proven helpful to collect and hold the items in transparent zip-lock bags for distribution. The students should also have been provided with a printed psychrometric chart during previous class times, which they can conveniently consult during the experiment (MacGyver would find an old copy inside the cover of the air handler).

As the instructor and supervisor conducting the experiments in a competition format, a digital thermometer/hygrometer (Figure 3a) should be at hand to judge the different teams in terms of who came a) closest, or b) fastest, or c) most creatively to their final solution. Furthermore, rather than having students resort to using just any liquids they have around, it is helpful to have a bottle of water readily available for students seeking to wick their pads. This water should be as close as possible to room temperature as it otherwise distorts and/or prolongs the process of obtaining useful results.

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[3] the paper clip is useless in this scenario and just added as a distraction – but there just has to be a paper clip somewhere in McGyver episodes.

Most of the commonly available exterior thermometers have a less exposed liquid bulb, which can make the assembly of a wet bulb thermometer more challenging and less effective. By breaking off the bottom area of the plastic holder (a set of pliers can make this a more controlled endeavor), the bulb can be exposed and will be thus directly accessible for the wet gauze pads and rubber bands (Figure 3b.)

a) b)

Figure 3. a) digital thermometer and hygrometer for use by supervisor; b) half-broken analog thermometer handed out to student teams

Experiment Execution and Discussion

While the students have to identify the purpose of each item by themselves, it helps if they observe other teams in their pursuit. There is usually one team charging ahead, either with a student on board knowing about wet bulb thermometers, or just being creative with evaporation and connecting string and thermometer. To challenge critical thinking, the teams should not be allowed to access the internet during the experiment.

Once a team starts swinging their wet bulb thermometer above their heads, others observe that and usually quickly try to copy the effort (Figure 4). However, there are always some teams missing the wetting part assuming that the cooling effect comes from the convective heat exchange as a result from the movement in air. This, in turn, is a great learning experience, which allows for directly observing and comparing the cooling effect of the evaporation process to standard room temperatures.

Figure 4. Student teams explore their MacGyver-skills to assess RH in the space

There is one more challenge involved that was even observed when this exercise was carried out in a workshop with experienced educators and professionals. Obviously, educators quickly knew how to assemble and use a wet-bulb thermometer. However, in their enthusiasm to be the first to report results they overlook that there is only one thermometer at hand. To obtain relative humidity, they would need two temperatures – the dry-bulb temperature of the room, and the then acquired wet-bulb temperature. Teams that did not take note of the original (dry-bulb) temperature reading of the thermometer had to go back and dry their device to quickly get it back to room temperature in order to lookup the respective RH in the psychrometric chart.

PHASE 2: EXPLORING THE DEW-POINT

With a deeper understanding of relative humidity, wet-bulb temperatures, and effects of evaporation students can then be guided to explore the "limits" of the psychrometric chart – the saturation curve, more commonly known as condensation. While condensation is frequently observed in daily life, such as when forming on a window during colder seasons, or on the outside of a glass of ice-cold beverage, the direct relationship of the required ingredients is initially not that obvious to students.

To better understand the environmental conditions that lead to condensation of water vapor in the air on different surfaces and to relate observations back to the psychrometric chart, the following team-assignment has been developed. Theoretically, the set of experiments that are part of this assignment could be mostly carried out as an in-class experience. However, the exercises provide more opportunities for exploration as a team homework assignment.

As a team, they will have to determine the psychrometric characteristics of different air and moisture conditions by investigating the occurrence of surface condensation on different containers carrying water with different temperatures (Figure 5). Using a variety of provided digital thermometers and hygrometers, they have to investigate surface condensation risk for different air-moisture conditions, observe results for different surface temperatures, and document their observations supported by graphical representations in the psychrometric chart.

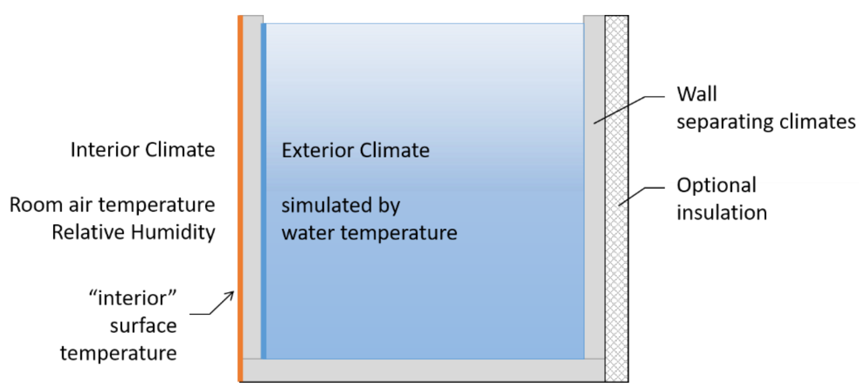

Figure 5. Container setup to create different "interior" surface temperatures

Materials, Equipment, and Preparation

The student teams are each provided with a set of tools that allows for various temperature and humidity assessment techniques: a contactless infrared (IR) thermometer gun, a submersible aquarium thermometer, and a digital weather station with a display for room temperature and relative humidity (Figure 6)

IR thermometers for this purpose can be purchased cheaply online, and are only used to determine surface temperatures of the utilized containers. If a variety of materials will be explored, an IR thermometer that allows for correction of emissivity is preferable. The required digital aquarium thermometer can be obtained from a local pet store, or also be ordered online for less than the price of a coffee drink. The thermometer should be water submersible to allow for temperature control of the “exterior” climate, which is replicated by the water temperature within a container. The digital room thermometer and hygrometer is used to assess the current interior air condition as a starting point for any interior surface condensation analysis. Overall, the total set of tools provided for each team could be obtained for $30 or less.

Figure 6. Items to be provided for dew-point experiments

Experimental Setup

The experimental setup should replicate assessing indoor air conditions against condensation risk triggered by different surface temperatures that are caused by exterior climate conditions.

The student teams have to investigate a mix of the different scenarios and air conditions. Specifically, they are encouraged to explore:

- Different air temperature conditions (e.g. room temperature vs. basement or refrigerator conditions)
- Different relative humidity levels (e.g. normal room humidity vs. a bathroom after the shower has been run for several minutes)
- Different thermal performances of the climate separating walls (e.g. glass container vs. Styrofoam cups or containers with a sponge sleeve)

Students are asked to create climate conditions with different containers (enclosure systems), different water temperatures (exterior climates), and different indoor air conditions. For each air condition, they are asked to record the indoor air temperature, the relative humidity of the air, the container surface temperature, and the "exterior temperature", i.e. water temperature. They then need to assess and record from a psychrometric chart or online tool the applicable dew point temperature and compare against their observations. They are encouraged to investigate different surface temperatures by changing the water temperature. E.g., starting with water at room temperature and gradually adding ice cubes to the water, which in turn will lower the surface temperature of the container. Once different "exterior" (water) temperatures were explored, they have to repeat the test with containers of different "wall" materials. For example, compare two containers with the same temperature of water, but different conductivity of material – one comparison could be a glass bottle or soda can with and without foam sleeve (Figure 7).

Experiment Execution and Discussion

When students conduct these experiments in class, instructor intervention typically prevents making major mistakes and at the same time improves the quality of results. However, conducting the experiments in their own residential settings can increase the learning outcome, if they decide to invest the time investigating in-conclusive observations. While graduate students usually are inquisitive enough to engage in this discourse, the reports generated from undergraduate teams typically show mixed results with several unaddressed mistakes made in the field. Discussing these mistakes through an in-class review can help in terms of how to detect and correct errors in their future careers.

a) b)

Figure 7. Assessment of surface condensation risk based on a) different "exterior" temperatures and b) different "wall" materials

Observed issues in different report submissions range from measuring errors to an incorrect understanding of observed principles. A frequent measuring error occurring when students utilize an IR thermometer is that they trust the laser pointer as the point of reference for temperature readings ignoring the optical cone that is formed by the lens, which drastically increases the area of measurement with increased distance to the object. Temperature readings then become a reflection of broader surface temperatures emitted by the environment rather than the location they were supposed to record. A second common error with IR thermometers is not understanding the underlying measurement principle and pointing it at reflective surfaces (e.g. glass bottles or aluminum cans). The typical emissivity of surfaces is expected to be between 90-95% for standard readings, so measuring surfaces with an emissivity of 10% are much more impacted by the surface temperatures of objects reflected by those. A quick fix for these situations could be applying a matt-finish tape on the surface before taking readings.

Incorrect assessment of dew-point temperatures from psychrometric charts is another place for errors. Students may follow the lines of wet-bulb temperatures as the "shortest" way to the saturation line and in turn do not find accordance between practice (experiment) and theory (psychrometric chart), as they overestimate the actual condensation risk. Other errors show how hard it is for students to comprehend the replicated principle, as they attempt to record surface temperatures inside the container pointing at the interior rim above the water surface or the water surface itself rather than the exterior container surface. Some students also ignore sequencing of the experiments by moving the container quickly in and out of a refrigerator or a humid bathroom and then observing transient short-term effects that do not match the steady state assumptions set forth for simple conductive temperature problems. The most critical errors observed were those where students reported inconsistencies that were ignored and/or not addressed, such as recording lower surface temperatures on the container than the actual water temperature or calculating dew-point temperatures significantly above room temperature without observing fog or rain in the same.

Overall, these experiments can contribute to a hands-on understanding of what happens when humidity laden air enters cavities of building enclosures and hits colder surfaces, be it the warmer interior air hitting the cold OSB sheathing during winter periods, or hot humid exterior air finding its way to the cooler interior gypsum layer in air-conditioned homes during summer times.

PHASE 3: EXPLORING THE INTERSTITIAL SPACE – VAPOR DIFFUSION

One of the most complicated concepts to comprehend in building physics is the principle of vapor diffusion. Diffusion not only happens through fibrous materials but also through otherwise "solid" materials, such as wood fiber or gypsum boards. While less critical in terms of quantity compared to condensate amounts from infiltration, diffusion can become a critical process that requires evaluation in terms of condensation risk and long-term damage potential, specifically in high-performing enclosures. The limited heat transfer in highly insulated wall systems, paired with a sharper drop of temperatures across these insulation layers can lead to interstitial condensation where vapor moves unrestricted while dew point temperatures quickly drop.

The relationship between thermal conductivity and vapor permeability is one of the most complex principles to understand, explore, and ultimately apply in practice. To provide a tangible context for this phenomenon, a third in-class (or lab) experiment has been designed to make the involved processes approachable.

The experiment is comprised of a chest freezer that is utilized to create a cold exterior (winter) climate. Different wall assemblies can be tested against this climate based on the current interior climate available in a space (Figure 8). The freezer lid is replaced by an insulation panel with an opening frame to receive different specimen holders. Specimen can be prepared in advance and quickly changed out with the various test assemblies from different teams.

Figure 8. Chest freezer reconfigured as a mobile environmental climate chamber

Materials, Equipment, and Preparation

The chest freezer can be an off-the-shelf appliance, which can be found in any of the common household stores. There are no specific requirements other than it should have a thermostat (which almost all do) for an opportunity to test against different "exterior" climates. Thermostats typically allow temperature settings between 30°F and -10°F. A 5-ft^3 volume freezer works perfectly well for the setup; a 7-ft^3 does not provide any significant advantage. While an even larger freezer may allow side-by-side comparisons when equipped with two openings, it may also lose its mobility to be move in and out of a classroom.

For the top-panel and specimen holders standard 2" XPS boards can be utilized, which are easy to cut with a table saw. A hot wire cutter is not necessary for preparing the XPS frames. The foam board can be glued with XPS compatible adhesives; it is recommended to check manufacturer requirements to achieve long-lasting, sturdy frames. To seal the joints between top panel and rim of the freezer, as well as the gap between specimen holder and top panel a roll of vapor-tight rubber foam weather-strip is required (Figure 9).

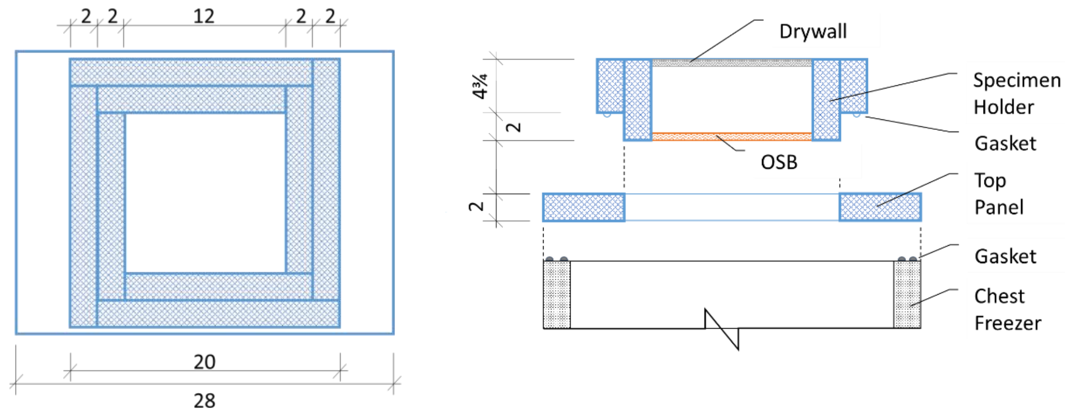

Figure 9. Top panel and specimen holder made of 2” XPS

The instrumentation for this experiment is accomplished with an Onset HOBO-ZW wireless node system, which allows for flexibility when moving the freezer into different locations. For this setup, a receiver node (ZW-RCVR) and preferably two 4-channel data nodes (ZW-005) are required. The ZW-005 already comes with a combined temperature and RH sensor and allows for the addition of two more analog sensors.

To obtain a full temperature profile across the entire assembly these other ports can be equipped with standard temperature probes (e.g. TMC6-HE). If more data points are to be collected, the system can be easily expanded by another 4-channel node. The data logging is actually done through a remotely connected computer that fetches the individual records from the different nodes through a USB connected receiver.

a) **b)** **c)**

Figure 10. a) HOBO ZW wireless node, b) air/water/soil temperature sensor, and c) HOBO ZW wireless receiver

While the setup discussed here is more expensive than the items utilized in the previous experiments, the equipment for the entire configuration can be purchased for less than $1,000 and could be financed at an institutional level, through an industry sponsor, or a fund-raiser organized by student chapters.

Experiment Setup

The top panel is cut from an XPS board and rests on foam weather strips that seal the freezer cavity against room air conditions. The specimen holders are also built out of strips cut from 2” XPS boards and glued together to hold a 1’x1’ wall assembly of up to 6.75” thickness (2x6 wall insulation cavity with ¾-in OSB and ½-in drywall) in this setup. Since the individual layers of the wall assembly are put in place horizontally and not vertically, as they would be in a wall, an edge trim element is mounted to the bottom to prevent the exterior sheathing from falling due to gravity. Furthermore, some small distance holders (e.g. balsa wood sticks) need to be placed in the corners to prevent compression of fibrous insulation materials when the heavier gypsum layer is placed on top of the assembly.

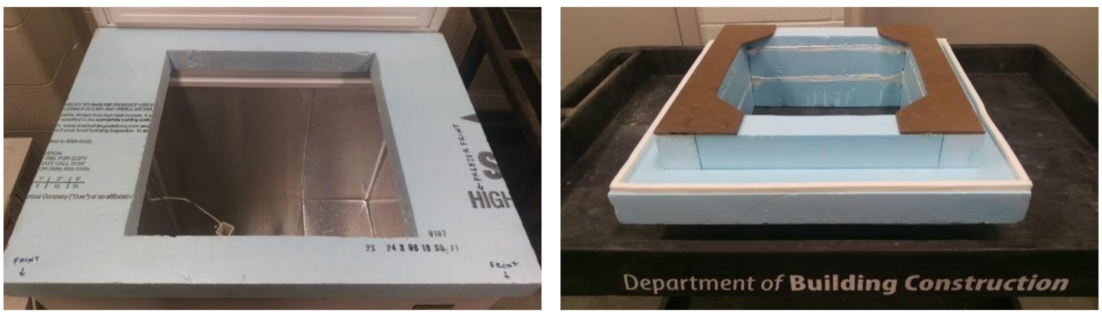

Figure 11. Top frame and specimen holder made of 2” XPS

It is helpful to have pre-cut (12”x12”) wall assembly materials such as OSB and gypsum boards at hand, as well as a variety of insulation materials (e.g. cellulose or faced fiberglass batts) to quickly facilitate the installation of wall assemblies in the prepared specimen holder. To allow for reusability of the specimen holders the use of removable sealants, such as TAP’s *SEAL 'N PEEL* or Red Devil’s *Zip-A-Way* sealants, is recommended.

Experiment Execution and Discussion

The experimental setup can even be finished during a class session, where students come up front to assemble and install their wall specimens. The setup in class also teaches students how to place and deploy a data-logging system. Students can be introduced to different sensor types and their installation requirements to capture various properties correctly. For example, the air/water/soil temperature sensors utilized in here have the tendency to be impacted by their radiant exposure when exposed to air. Thus to record surface temperatures correctly they must have a secure conductive contact with the respective surface and occasionally may require shielding from objects with higher temperature difference (e.g. radiant heat sources) in their surroundings.

An actual test cycle takes several hours to establish steady state conditions and thus exceeds a normal class period. However, initial results of an increase in relative humidity in the cavity can be typically observed within a couple of hours.

Figure 12. Installation of a sensor a) within freezer b) on the exterior OSB board and c) closing of the cellulose filled cavity with a gypsum board

Figure 13. Air sealing of the cavity with removable sealant on the exterior side and taping of the drywall joints on the interior side

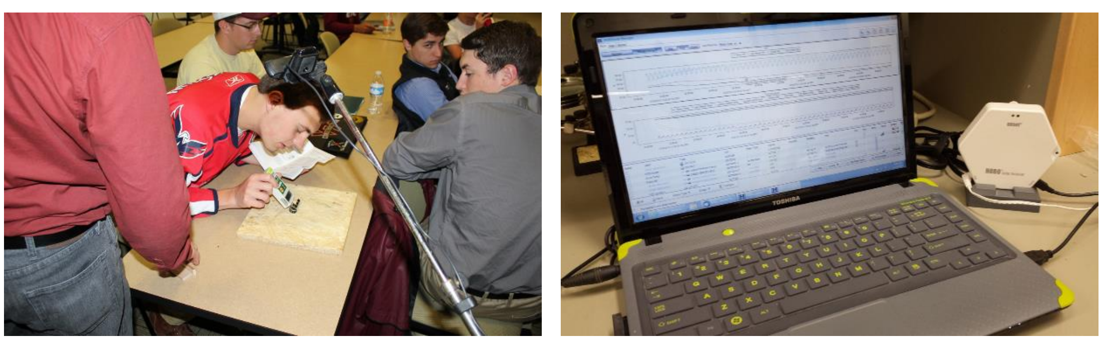

Figure 14. Measurement of initial moisture content of OSB board; and data-logging and monitoring station with wireless receiver

It is recommended to have a test run over several days. This demonstrates that while steady-state temperature conditions are typically achieved within 3-5 hours, there often is a constant increase of moisture accumulation within the cavity that eventually can trigger interstitial condensation build-up and consequently lead to rot and mold invisible from either side of the wall.

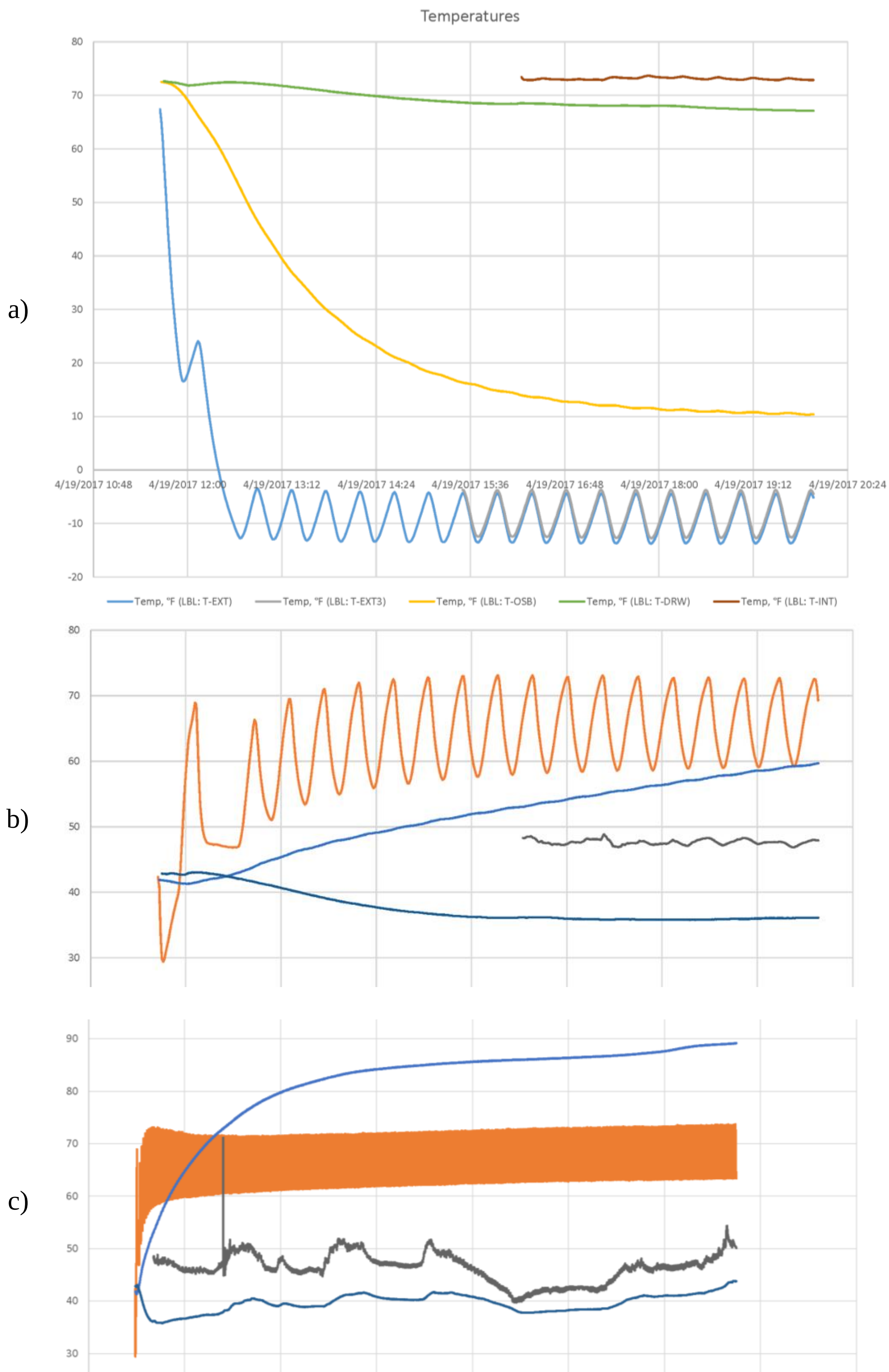

Figure 15. a) Temperature measurements over hours b) relative humidity measurements over hours and c) over days

CONCLUSION - ACHIEVEMENT OF LEARNING OBJECTIVES

The experiment series presented in here slowly introduces the student in an engaging and explorative way to psychrometric concepts of air movement and moisture control issues in building enclosures. While the first in-class experiment is mostly designed to gain some familiarity with the various properties of psychrometrics, it also teaches the challenges of actually obtaining real measurements in a qualitative relevant way. It is highly likely that no team will come close to the actual relative humidity in the space, which in turn becomes a lesson learned in measurement accuracy and trust related to the evaluation of obtained results. The second experiment series challenges students to link real-world observations with theoretical knowledge. However, the abstraction of recreating environmental boundary conditions by utilizing a different medium than air does not work with all students equally well. It requires them to think outside the box to connect the scenario with conditions that can occur through infiltration of gaps in exterior walls, and the condensation risk that such air movements represent.

Figure 16. Insulation frozen to the OSB and build-up of ice from interstitial condensation

The final experiment, while studying the most complex physical relationships of the series, delivers the most unsettling response. When students participate in opening the wall, and encounter the insulation material frozen to the OSB or touch actual ice-buildup on the exterior side of the cavity, this provides a lasting learning experience. It is the hope of the authors, who are also instructors of a building physics course, that this impression lasts for a lifetime, so that when our graduates are out in the field and are confronted with new material combinations and different environmental conditions, that they are aware of the many factors that contribute to a well-managed and constructed high-performance enclosure system.

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