Hygrothermal Performance of Residential Cantilevered Floors

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Dedication

My father, Harold Stone, taught me that details matter and work should be done well.

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Rick Wheeler taught me about the art of building diagnostics by his example.

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Abstract

This field investigation was designed to compare three insulation strategies commonly used in residential cantilevered floors. The first objective is to determine floor surface temperatures above insulated cantilever cavities, with respect to occupant thermal comfort. The second objective is to determine moisture behavior within insulated cantilever cavities, with respect to durability.

The experimental set-up was installed in the cantilevered floor of an existing Minnesota home. The first six months of investigation, from mid-summer into early winter, provided data for analysis and discussion presented in this thesis.

Investigation results support the view that cantilevered floor cavities open to adjacent conditioned space have warmer floor surfaces above them. Condensation and wetting in some cantilever cavities during colder weather suggests that durability risks are increased in cavities where there is air movement through the thermal insulation. Further investigation is expected to provide a more comprehensive representation of the annual hygrothermal cycle.

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Chapter 1

Introduction

Background and History

The cantilevered floor is an architectural feature where the floor extends a short distance beyond an exterior wall that supports it from below. The extended floor supports an exterior wall at its outer edge. The cantilevered floor has also been identified by other names such as a floor over unconditioned space, overhang, garrison style floor, cantilevered overhang, extended rim joist, jettied floor, and overhanging floor. This type of overhanging floor is commonly used in the design of homes to give a residential building greater curb appeal, extend the size of a room, or provide extra space extending beyond the main part of a room for a bay window, closet, or gas fireplace. *(Figure 1)*

Figure 1. Cantilevered second story floors and cantilevered bay window

Figure 2. Multi-family housing with cantilevered third story floors

Multi-family wood-frame construction frequently incorporates cantilevered floors to break up large expanses of wall and add visual interest. *(Figure 2)* Related building features identified as "floors over unconditioned space" include attached sunrooms supported above the ground on piers *(Figure 3)* and rooms framed into attic spaces over garages. They are supported differently than cantilevers but require similar insulation and air-sealing details because their floors are suspended over unconditioned space. While there may be building performance lessons learned from this study that could be applied to other types of extended floors, this study will focus on a cantilevered floor in a cold climate that projects two feet beyond its supporting wall.

Figure 3. Attached sunroom on piers

The cantilevered floor is not a recent architectural feature in buildings. Timber framed wooden buildings with cantilevered floors have been constructed in Asia, Europe, and North America for hundreds of years. The oldest wooden tower in China, the Fugong Temple Pagoda in Shanxi province was constructed in 1056 AD using log walls supported on cantilevered timber floors at each level. (Gisling 2007) *(Figure 4)* A European example of cantilevered timber floors can be seen in a double-jettied medieval English building in Lincoln, Lincolnshire. (Dunn 2004) *(Figure 5)* The squared timber floor joists can be seen under the supported walls of both structures when viewed from the exterior.

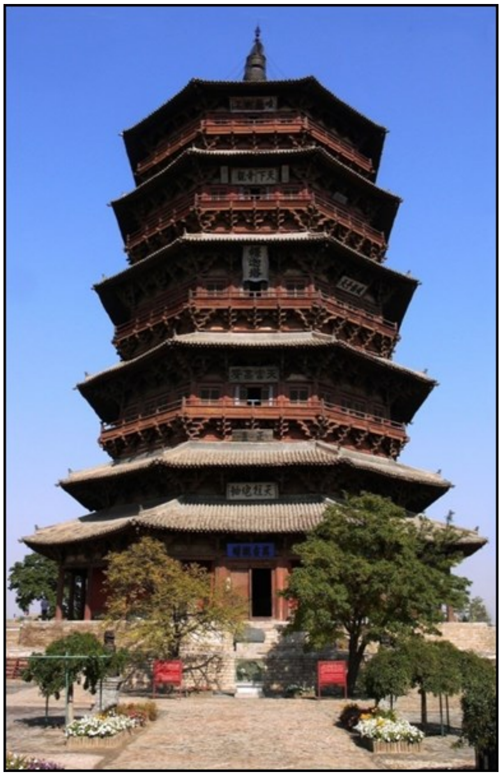


Figure 4. The Fugong Pagoda, 1056 AD (Gisling 2007)

Figure 5. Lincolnshire double-jettied timber building (Dunn 2004)

While timber construction created strong, durable structures, the solid wood provided minimal resistance to heat loss, resulting in cold floors. *(Figure 6)*

Figure 6. Uninsulated timber floor in Green Lake, WI

A significant change to new home construction in cold climates over the past decades has been increased levels of installed thermal insulation combined with increased attention to building cavity air-sealing details. The introduction of the balloon and platform styles of frame construction created building cavities in wall and floor assemblies that could be filled with insulation, potentially increasing resistance to heat loss. The integration of engineered structural components like floor trusses and composite materials, like fiberboard and oriented strand board, into frame construction has made it possible to increase the dimensions of building cavities to hold even more insulation. A number of recommended methods for insulating and air-sealing the overhanging floor assembly can be found in popular construction and building science literature. A variety of different approaches are employed as standard practice in cold climate homes. Each of the recommended or applied methods is intended to optimize insulation levels based on an interpretation of previous building experience, the principles of building science, or a combination of both. Increasing the levels of insulation has raised the expectation of increased comfort by homeowners while the product and process changes employed to achieve increased comfort may hold the potential to contribute to a reduction in the long term durability of residential buildings. A cantilevered floor, projecting over unconditioned or ambient space also adds more exterior surface area to the heating and cooling load of the conditioned room above it. *(Figure 7)* The method selected to insulate and air-seal the cantilever floor, the overhanging part of the assembly, may also include intentional or unintentional thermal and pressure connections to the conditioned or partially conditioned rooms that are below the floor that is extended. In cold climates, increasing thermal insulation in building cavities reduces the interior surface temperature of the exterior sheathing and nearby framing members and increases

Figure 7. Exterior view of cantilevered floor during construction

the potential for condensation and frost formation when moist air from inside the building enters insulated building cavities and comes into contact with those colder surfaces. The infiltration of moist air is accompanied by the threat of extended wetting cycles that could result in damage to the building's wood-based structural components. Increased levels of thermal insulation reduce energy bills for homeowners, but they also reduce the energy and air movement available to dry enclosed building assemblies that have become wet.

The decision to take a closer look at the cantilevered floor comes from several years of field observation while working with builders as a representative of several residential energy programs. During site visits with builders and insulators, extended floors were frequently the subject of intense discussion, as a number of "correct" methods to complete the assembly have come to be taught, promoted and implemented. The differences between these various methods fall into three representative strategies for insulating and air-sealing the assembly. The three methods, or styles, most commonly seen in new or existing homes that have insulated cantilevered floors are:

1. All joints and seams of the cantilever overhang are air-sealed. The framed cantilever cavity is filled partially with a fiberglass batt at the bottom and rim joist, but without blocking installed between the insulated cantilever assembly and the uninsulated floor from which it extends. *(Figure 8)*

Figure 8. Cavities partially filled with batts

2. Closed cell foam insulation is spray-applied against the exterior cantilever rim joist and across the bottom of the cantilever cavity. The foam insulation extends fully over the top of the exterior wall that supports the cantilever and air-seals all joints and seams in the framed cantilever overhang cavity. *(Figure 9)*

Figure 9. Spray applied polyurethane foam

3. All joints and seams of the cantilever overhang are air-sealed. The framed cantilever cavity is filled completely with fiberglass batts *(Figure 10)* and solid blocking is then air-sealed in place between the insulated cantilever assembly and the uninsulated floor from which it extends. *(Figure 11)*

Figure 10. Cavities filled completely with batts

Figure 11. Cavities blocked and air-sealed

Infra-red thermography is a tool used to show surface temperature differences during inspection of new or existing homes. One commonly used IR display option shows warmer areas as lighter and colder areas as darker. An interior thermograph of a cantilevered floor (previously shown from the exterior in *Figure 7*) identified ceiling surfaces below this particular cantilever floor assembly that appear much colder than adjacent wall surfaces and floor framing. (*Figure 12*) When this thermograph was taken, the areas were colder due to blower door induced air leakage, or infiltration, of cold, winter air from outside during a new home commissioning process. When under normal winter operating conditions, this cantilevered floor area could experience either infiltration or exfiltration through the leaky framing of this assembly depending on the current wind direction and intensity. Infiltration could dry the cantilever by bringing colder, drier air into the house while exfiltration could wet the interior of the cantilever assembly by driving warmer, more humid indoor air from inside the home out into insulated building assemblies. While infra-red inspection provides a snapshot of the surface temperatures of materials surrounding a cantilever floor assembly, it does not provide the detailed information about cantilever cavity interior temperature and moisture conditions and boundary conditions that are needed to see a more complete picture of the hygrothermal performance of cantilevered floors.

Figure 12. Thermograph of cold ceiling surfaces below the cantilevered floor

Objectives and Approach

The goal of this work is to expand the body of knowledge about the interior temperature and moisture conditions in cold climate cantilevered floors. Because the cantilever, or insulated floor that extends over unconditioned space, is being completed by such a variety of methods which place the thermal insulation, vapor retarder, and air barrier in different configurations, these question are raised:

1. Will insulating and air sealing cantilevered floor assemblies by different methods result in floor temperature differences above the cantilever that may have an impact on occupant comfort?
2. Will insulating and air sealing cantilevered floor assemblies by different methods result in different moisture conditions within the cantilever assemblies that may have an impact on building durability risks?

The process of addressing these questions began with a literature survey that searched online homeowner forums for questions regarding cantilever floor comfort and durability, online building contractor and building science forums for questions regarding cantilever floor construction details and durability. Construction industry and building science textbooks, technical references, and Minnesota energy and building codes were reviewed for detailed guidance regarding the cantilevered floor assembly. Previously published investigative works on topics including cantilevered floors, hygrothermal behavior/performance in wood frame buildings, wood moisture content in building assemblies, software tools for temperature and moisture analysis, and instrumentation design and installation for the field monitoring of temperature and moisture in wood-framed buildings with cavity insulation were reviewed for the relevant guidance they might provide during the design and execution of this investigation.

Next, a test methodology was developed to determine if differences in floor temperature and/or moisture conditions could be found in a side-by side comparison of cantilevered floor assemblies that employed three different insulation and air-sealing strategies in the same cantilevered floor in an existing, occupied house. The investigation results were evaluated to address these comfort and durability questions:

1. Did different insulating and air sealing strategies for cantilevered floor assemblies result in significantly different floor temperatures when compared side-by-side during the coldest outdoor conditions monitored and recorded during the six month investigation period?
2. Did different insulating and air sealing strategies for cantilevered floor assemblies result in significantly different moisture conditions, with regard to building durability risks within the cantilevered floor assemblies, when compared side-by-side during the six month investigation period?

Chapter 2

Literature Survey

Online Sources and Industry Periodicals

Cantilevered floors add exterior surface and the potential for heat loss from a house in addition to the added complexity of framing, air-sealing, and insulating the overhanging floor assembly. An online search for cantilever problems easily turned up a homeowner forum complaint of moisture condensation and frost build-up that was found in insulated cantilever floor cavities after water damage to walls resulted inside the house below the overhanging floor. (cgingras, 2007) HGTVremodels, an online forum for homebuilding professionals that includes discussions of problems like temperature, comfort, and moisture concerns, claims that “If a cantilever isn’t properly sealed, it will leak air, causing the floor to feel cold. Condensation is the worst result of air leaks in cantilevers. Moist air in the home can pass into the floor cavity and condense on the coldest surface it finds – the backside of the sheathing or band joist – causing mold to grow there.” (HGTVremodels, 2009)

Online forums are not alone in responding to cantilever issues. The Canada Mortgage and Housing Corporation has published an online article for homeowners on insulating floors over unheated spaces that includes paragraphs on benefits, considerations, implementation, and payback. (CMHC, 1996) An online article by Martin Holladay gives step by step instructions and clear graphics for construction professionals to follow when insulating and air-sealing a cantilevered assembly by filling it with fiberglass batts, then blocking and sealing it at the interior. He also points out that there are many ways to insulate a cantilevered floor. (Holladay, 2012) Manitoba, Canada's R-2000 program offers detailed graphics for four insulation options along with advantages and disadvantages of each in the 'Technical Corner" pages of their website. (R-2000, 2000)

Home Energy, The Builder's Digest, and other periodicals that serve the construction and home performance industry have also published articles by other authors (Cheple, 1998) (Stone, 2009) (oikos, 1997) (Tooley, 1999) that provide detailed descriptions, graphics and photos of methods used when completing insulating and air-sealing in cantilevered floor cavities.

Textbooks

As with the magazines and online sources, the method most often promoted in textbooks is that in which the cantilevered floor cavity is completely filled with fiber glass batt insulation and closed off with solid blocking and air-sealed. (CHBA, 1989, p.99-100) (Legg, 1997, p.165) *(Figure 13)*

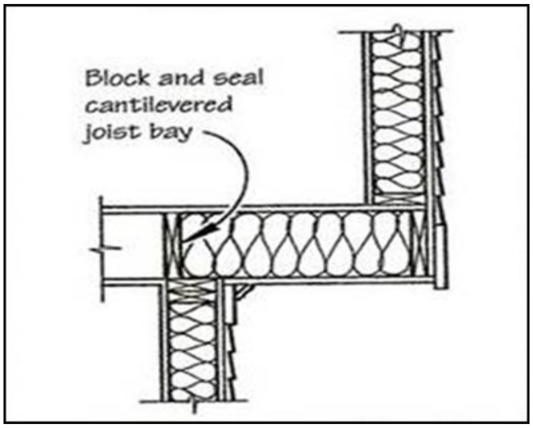


Figure 13. Filled, blocked, and sealed cantilevered floor (Legg, 1997, p.165)

Because of the age of Minnesota's housing stock, insulated cantilevered floor cavities are most often found to be partially filled with fiberglass batts at the bottom and rim joists, but without blocking installed between the insulated cavity and the uninsulated floor from which it extends. Only one literature reference to this method was found, and that was in a 1992 edition of a carpentry textbook that was first published in 1969. The text devotes only four sentences to insulating the cantilevered floor assembly. One advises to insulate the floor projection, one describes how to attach the faced batt in position across the bottom of the cantilever and against the rim joist. *(Figure 14)* The remaining two sentences suggest how to do this more simply. (Wagner, 1992, p.343) No mention is made about air sealing the cantilever assembly. References to cantilevered floors reviewed in older texts describe only framing details and do not provide insulation or air-sealing instructions.

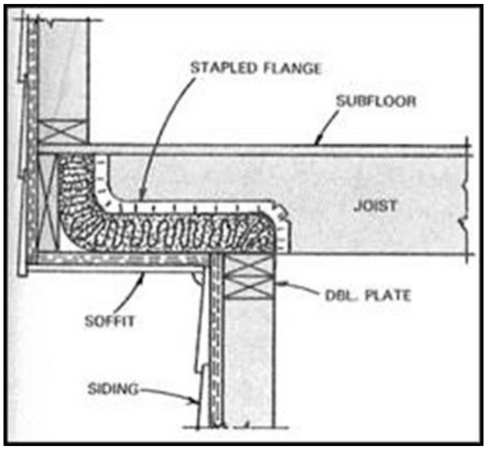


Figure 14. Batt at bottom and rim joist (Wagner, 1992, P.343)

Support for this open style has been vigorously maintained by builders and insulators who offer the opinion that warm air from below must be allowed to flow up into the airspace between floor joists and above the batt to warm the floor above.

Energy Codes

Of the three styles described previously in this paper, the fully filled, blocked, and sealed method is the only one of the three that is in compliance with Minnesota's Residential Energy Code for new construction at the time of this writing. Table N1102.1 in IRC SECTION N1102, BUILDING THERMAL ENVELOPE lists the required R-value for floors as R-30, with the exception (d) "Or insulation sufficient to fill the framing cavity, R-19 minimum." In addition to the required R-value of 30, section N1102.2.5 requires that "Floor insulation shall be installed to maintain permanent contact with the underside of the subfloor decking." Lastly, section N1102.4, on air-leakage, requires that "The building thermal envelope shall be continuously sealed to limit the leakage of air through the thermal envelope. The air barrier shall be installed on the warm-in-winter side of the thermal insulation. Areas of potential air leakage in the building thermal envelope shall be caulked, gasketed, weatherstripped, or otherwise sealed with an air barrier material to form an effective barrier between conditioned and unconditioned spaces. The integrity of all air barriers shall be maintained. The sealing methods between dissimilar materials shall allow for differential expansion and contraction. The following shall be caulked, gasketed, weatherstripped, or otherwise sealed with an air barrier material, suitable film, or solid material:

1. Walls, floors, ceilings, overhangs, kneewalls, and floor rim joist areas separating conditioned from unconditioned spaces." (MN Chapter 1322, 2009)

To put this into perspective, a 2x10 joisted cavity filled completely with standard insulation batts would provide approximately R-30. The R-30 batt will not hold enough "loft" to stay in contact with the underside of the subfloor, so additional fiberglass batt material must be added to keep the cavity full and in contact at the top. The cavity air-sealing, insulation, blocking, and air-sealing of the blocking in place all need to be done exquisitely to create a fully insulated cavity with a completely effective air barrier. Now, consider alongside of that requirement that this type of work is not seen as very pleasant and is usually assigned to the last hired, least trained member of the insulation crew.

Foam Insulation

Spray-applied plastic foam insulations have been used in both commercial and residential applications for decades. The past several years have seen an increase in the use of foam insulations in residential applications as the price has become more competitive and more formulations are competing in the market. Closed cell foam is frequently used in rim and band joist locations because it provides the insulation, the vapor retarder, and the air barrier in a one-step application. It has also become a popular method of insulating and air-sealing cantilever floor assemblies for the same reasons. The Builder's Guide to Cold Climates includes a graphic illustration of the spray-applied foam insulation method used when insulating cantilever floor assemblies. *(Figure 15)* The same page also contains an illustration of the cantilever insulation and air-sealing method that uses fiberglass batts combined with sealed blocking. (Lstiburek, 2004a, p. 278)

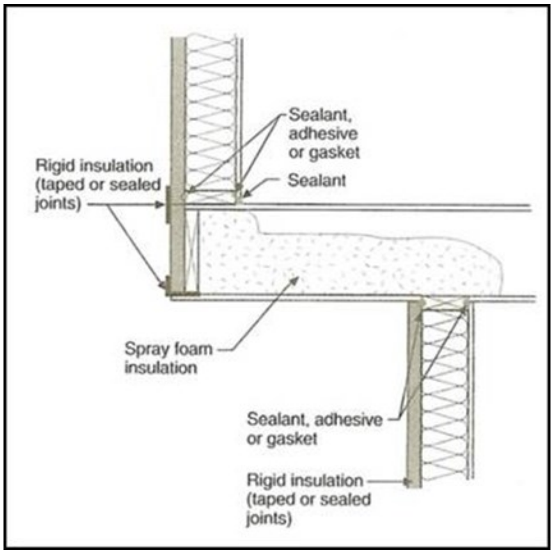


Figure 15. Cantilevered floor with spray foam insulation (Lstiburek, 2004a, p.278)

The Consortium for Advanced Residential Buildings – Steven Winter Associates, Inc. provides material properties and performance characteristics for a number of the plastic foam formulations currently being used to insulate buildings. Their evaluation includes foam insulation performance for a variety of building assemblies and in several climate zones. Cantilever floors and floors over unconditioned space are specifically addressed by the article. (CARB, 2009)

A Canadian field study comparing open cell and closed cell foams in walls found that "open cell SPUF walls had insufficient vapour resistance during the winter in Southern Ontario's climate at interior conditions of 20° C and 50% RH to keep sheathing moisture contents below 20%, particularly on the north orientation which had moisture contents above 30% for a few months. The closed cell SPUF walls however did have sufficient vapour resistance to maintain sheathing moisture contents below 20% for the same interior conditions. (Finch, 2007)

Current Minnesota building codes restrict closed cell plastic foam to a maximum of 5 ½ inches in the rim joist location in addition to setting flame spread and smoke development limitations on foam products used in that location. (MN Chapter 1309) All of the Minnesota energy code requirements, including R-value, location of insulation, and air-sealing that were described earlier in this paper also apply to the use of foam insulation products.

Air – Sealing

The building science community has thrown its support behind air-sealing to prevent the movement of warm, moist air between conditioned and unconditioned spaces. Concern that the foundation "might redirect moisture to the band or rim joist" is raised in a Minnesota study of energy and moisture issues in basements. (Huelman, 2004) Oak Ridge National Laboratory, in collaboration with Washington State University's Natural Exposure Test Facility, studied "Damage caused by uncontrolled moisture accumulation in building enclosures" using a combination of field testing and hygrothermal modeling.

(Karagiozis, 2003) While this article dealt primarily with water from the outside and studied moisture dynamics and drying potentials with comparisons to modeling, an earlier paper by Karagiozis is more focused on the effectiveness of the air barrier and states that “Infiltration can contribute significantly to the overall heating or cooling load of a building and is directly dependent on environmental loads, envelope design and operation, and construction workmanship. Uncontrolled construction infiltration / exfiltration is a[sic] common in residential buildings and influences the indoor air quality, building energy consumption and durability of a building. Of the three above listed impact areas of infiltration / exfiltration airflows, the least understood is the influence on the durability (hygrothermal influence), followed by the influence on thermal performance.” (Karagiozis, 2001a) Air leakage through a cantilevered floor was encountered by Kohta Ueno in a research home used for his M.A.Sc. thesis research. He observed that “At the cantilever bays, there was no air barrier in the joist bay between the interior and the cantilever”…“and the air barrier at the cantilever (to exterior) is very poor, due to access/detailing difficulties. As a result, there is a substantial cold air leak at the cantilever bays[.]” (Ueno, 2007) This anecdote adds weight to the construction workmanship comments about air barrier integrity by Karagiozis. Several additional articles on the topics of air barriers, vapor retarders (and vapor barriers), and moisture control in buildings were reviewed in an effort to better understand moisture transport mechanisms and identify control strategies particularly relevant to the cantilevered floor assembly. (Bomberg, 2002) (Chown, 2000) (Goldberg 2010) (Lstiburek 2004b)

The one article found in this survey that was the most relevant to the cantilever assembly was prepared for the Minnesota Department of Commerce following almost two years of investigation at the University of Minnesota's Cloquet Residential Research Facility focused on foundation and rim joist insulation and air-sealing methods. (Goldberg, 2002) The Cloquet facility is located in DOE climate zone 7 (very cold climate) and rim joists and extended rims (cantilevers) are similar building assemblies, especially with regard to location in the building enclosure.

Wood Moisture Content

The measurement of wood moisture content is well recognized test method used to determine the durability risk of wood building assemblies. But, at a recent BEST2 conference, one paper pointed out that "measurement of moisture content of wood and other materials is incidental to the main question having to be answered. For whatever reason questions were raised that required an investigation, the main goal is to decide whether or not there is a potential problem, and to decide what to do about it if there is a problem." (Onysko, 2010) In the case of this study, that reason is exactly to determine if there are comfort or moisture problems. "Many building materials have the ability to absorb moisture. In a well-designed building, moisture absorption in building materials should not be a concern; however; excessive moisture content of some building materials can lead to premature deterioration and even failure." (Trechsel, 2001)

How to determine when there is a problem, parameters must be established. "Serious decay occurs only when the moisture content of the wood is above the fiber saturation point (average 30%). Readings of moisture content over 20% are considered to indicate danger of decay because average readings are generally higher than some single readings. Only when previously dried wood is contacted by water will the fiber saturation point be reached. Water vapor in humid air alone will not wet wood sufficiently to support significant decay, but it will permit development of some mold on the surface. Fully air-dry wood usually will have a content not exceeding 20% and should provide a reasonable margin of safety against fungus damage." (Sherwood, 1994, p.80)

Understanding how boundary conditions impact the potentials for wood moisture content is also important. "Seasonal changes in outdoor temperature were found to produce seasonal variations in the moisture content of the outer layers of a wood-frame wall. The most important parameters affecting the amount of moisture accumulation during the winter were the indoor relative humidity and the outdoor climate. Indoor relative humidity was observed to be more important than outdoor climate. The amount of moisture accumulation was greater in colder climates." (Burch, 1991)

Software Modeling Tools

While there is not a software modeling component of this study, a number of articles on software modeling tools that are used to predict temperature and moisture behavior in wood-frame building assemblies were reviewed for the general guidance they might provide during the planning of this work. (Karagiozis, 2001b) (Straube, 2002a) (Mukhopadhyaya, 2003) (CMHC, 2003) "Although controlled laboratory studies are a useful part of developing and benchmarking computer models, the ultimate test is a comparison to the measured performance of a building in use. Both test house data and real building data can be used to benchmark models, with each having their advantages and disadvantages. Test house data tends to be more detailed with more accurately controlled boundary conditions. Field measured data tends to be of less quality and less comprehensive, but includes all of the uncontrolled effects of real building use.” (Straube, 2003)

This study will focus on field measured data from a house that is in use as a residence with the expectation that the data, while it may be influenced by the many uncontrolled conditions found in a functioning residence, will provide some useful answers and possibly bring shape and direction to any new questions raised.

Instrumentation Design

Configuration of sensors in the test cavities was one of the primary concerns during the planning for this study and the topic most vigorously tracked down during the literature survey. No previous publications on the cantilever floor were found, so sensor configurations in wall and roof assembly studies were examined to determine the types of measurements taken in studies with related goals. Sensor sourcing, optimal placement of sensors within cavities, and the layout of test cavities and buffer (or guard) cavities were also examined in the articles reviewed. Graphing of data and interpretation of results were also studied. (Carll, 2007) (Straube, 1997) (Smith, 2007) (Tichy, 2006) (Zhang, 2006) The studies reviewed were consistent with regard to sensor layout, but Straube made it clear in one paper that “In almost every case (especially in research projects) the measurement of boundary conditions is vital for gaining the most value from measurements within the enclosure being studied.” (Straube, 2002b)

Two other articles contained gems that made a significant difference in the build-out phase of this study. Questions about the protection of the sensors in the cavities, particularly during the spray-application of closed cell foam over the instruments, were answered in the detailed description of sensor preparation and installation that included the use of Tyvek enclosures for sensors. (Black, 2006) This housewrap enclosure, because of its physical properties, protected the instruments from being filled with plastic foam and rendered useless while still allowing them to effectively measure temperature and humidity. The second important piece of information had to do with moisture content measurement in the Douglas Fir plywood subfloor across the top of each test cavity. A Forest Products Lab article revealed information from an earlier paper (Bell, 1949) that glue in plywood laminations could be an electrical conductor and should be tested using a resistance meter and "observing the meter reading as the electrode pins are driven into and then through the first ply. If the meter shows an abrupt increase in reading as the pins contact the glue line, moisture reading on that plywood will be unreliable. If no such effect is noted, the glue will not affect the readings." (James, 1963) The plywood sub-flooring in all test cavities was tested before proceeding to confirm the ability to measure wood moisture content reliably at those locations.

This literature survey was able to find numerous descriptions of cantilever assemblies and instructions on the insulation (and in some cases, air-sealing) of the cavities, but was unable to locate previous research conducted specifically for the purpose of determining temperature and moisture conditions within the cantilever during cold climate seasonal changes and comparing multiple insulation strategies.

Chapter 3

Research Design and Set-up

Research Site

The house used for the field study is a raised ranch-split entry three bedroom wood frame structure built in 1971 in Roseville, Minnesota. It is located on well drained building site at an elevation of 288.036 meters (945 feet) and located in DOE climate zone 6 (cold climate). The main level has 2x4 exterior walls with R-11 fiberglass batts in the cavities and 4 inches of loose fiberglass insulation, rated at approximately R-10, in an attic space over a flat ceiling.


Figure 16. Test house with cantilever on north side

The main floor of the house is cantilevered two feet beyond the north look-out basement wall for the full 26 foot width of the house. *(Figure 16)* The cavities of the cantilever floor assembly are accessible from the interior of the unfinished mechanical room in the north half of the basement. The floor joists are 2x10 Douglas Fir and extend across a 2x6 sill plate at the top of a full height12 inch cement block wall with the top cores sealed.

Below the overhang, the above grade exterior of the foundation wall is covered by a 2x4 uninsulated frame wall. The interior of the basement wall is not insulated. The cantilever cavities were partially filled with Kraft faced fiberglass batt insulation and there was no blocking or air-sealing where the cantilever floor cavities meet the uninsulated floor above the basement wall *(Figure 17)*

Figure 17. Interior of the cantilever in 'as found' condition (west side)

The mechanical systems include an 85% AFUE natural gas forced air furnace (with 2½ ton central air conditioning), a 65 gallon atmospherically vented natural gas water heater, and a portable Santé Fe dehumidifier located in the northeast part of the basement. Most of the house is kept around 20° C (68°F) in the winter and 24°C (75°F) during the summer. The mechanical room is not fully ducted and is cooler than the rest of the house during all seasons. There is a wood-burning fireplace in the basement level of the house which has been used only once in nine years. Relative humidity inside the house is maintained at approximately 35% during the spring, summer, and fall. The house becomes drier than that during the winter months due to natural ventilation (infiltration and exfiltration).

The building has 2415 square feet of conditioned floor space, 5305 square feet of surface area separating conditioned from unconditioned space, and a conditioned space volume of 20,616 cubic feet. A blower door test of the house in May 2008 showed leakage of 2160 cfm50 or 0.41 cfm/ft^2 surface area. In February 2011, after blocking and air-sealing large bypasses around the double-wall metal chimney, the main plumbing vent stack, and the kitchen exhaust fan ductwork, the house was tested again and showed leakage of 1787 cfm50 or .34 cfm/ft^2 surface area, a 17% leakage reduction under blower door test conditions. Both of these tests were conducted before changes were made to the cantilevered floor for the field study.

Based on existing construction details found in the cantilevered floor during the set-up for the field study, it was expected that the air-sealing completed in the floor cavities during the field study set-up would result in a measurable reduction of air leakage. In March 2014, after completing the modifications to the cantilevered floor for the study, a blower door test of the house showed leakage of 1742 or .33 cfm/ft^2 surface area. This was almost a 3% additional reduction from the original 2160 cfm50 or a combined leakage reduction of almost 20% under blower door test conditions.

Layout Conditions and Decisions

The 2x10 Douglas Fir joists for the cantilevered floor on the north side of the test house had been framed at 16 inches on center and extend across a 2x6 sill plate. A double 2x10 rim joist extends the full 26 feet across the north end of the floor joists. There are twenty joist cavities, eighteen of which are open and accessible from the basement. For identification during the study, the accessible cavities were numbered from 1 through 18, beginning at the west end. The two inaccessible joist cavities above the east and west block foundation walls were not included in the numbering sequence. Installed on top of the joists is a three quarter inch Douglas Fir plywood sub-floor. Three quarter inch thick oak flooring is installed over the sub-floor in both rooms above the cantilevered floor area and carpet is installed over the oak flooring in the northwest room.

The bottom of the exterior part (soffit) of the cantilevered floor assembly was three eighth inch exterior Douglas Fir plywood. Because wood moisture content would be measured by pins set one fourth inch into the soffit exterior finish material, which would result in the measurements being taken closer to the exterior than the interior if the existing plywood was used, the decision was made to look at an alternative that would move the tips of the wood moisture content pins inward at least to the center of the soffit material. In the 2005 ASHRAE Handbook of Fundamentals, the R-value of three eighth inch fir plywood was found to be .47 and the R-value of one half inch thick Douglas Fir lumber was calculated to be .495. (ASHRAE, 2005) The small difference would not significantly impact temperature trends recorded and would allow the moisture content pin tips to be held to the inside half of the soffit test panel. Forest Products Supply, Inc. of Maplewood, MN produced six twelve inch by sixteen inch by one half inch panels of clear, vertical grain Douglas Fir to be used in the center of the soffit location (bottom) of the test cavities. The panels were glued up from individual boards at least three inches wide, avoiding the placement of glue joints in the center four inches of the panels where the moisture content pins would be installed.

The other plywood issue to be resolved was the possible glue conductivity in the three quarter inch Douglas Fir plywood subfloor at the top of each test cavity. Beginning from the bottom of the subfloor in each cavity, the three quarter inch plywood was tested, using a Lignomat Ligno-VersaTec moisture meter and E14 wood moisture probe to determine if the glue used in the plywood had electrically conductive properties. The E14 pins were slowly pushed into the plywood subfloor from below while monitoring the meter for a spike in the reading which would indicate that the glue was electrically conductive. All readings taken in each test cavity were normal for Douglas Fir and no meter readings indicated unusual conductivity in the subfloor plywood.

The joist configuration made it possible to plan for three insulation configurations of three cavities each on each half of the extended floor. The three insulation configurations used were the three types described previously in this paper:

1. All joints and seams of the cantilever overhang are air-sealed. The framed cantilever cavity is filled partially with a fiberglass batt at the bottom and rim joist but without blocking installed between the insulated cantilever assembly and the uninsulated floor from which it extends.
2. Closed cell foam insulation is spray-applied against the exterior cantilever rim joist and across the bottom of the cantilever cavity. The foam insulation extends fully over the top of the exterior wall that supports the cantilever and air-seals all joints and seams in the framed cantilever overhang cavity.
3. All joints and seams of the cantilever overhang are air-sealed. The framed cantilever cavity is filled completely with fiberglass batts and solid blocking is air-sealed in place between the insulated cantilever assembly and the uninsulated floor from which it extends.

Each of the three cavity insulation configurations included a guard cavity on either side of the test cavity. The east and west halves of the cantilevered floor each contained nine cavities, with three of them being test cavities. The two halves were configured in a mirror image of each other, like bookends. Using the numbering system described above, the designated test cavities were #2 (R-19 batt open to the basement), #5 (Foam insulation), #8 (R-30 batt, blocked and sealed), #11 (R-30 batt, blocked and sealed), #14 (Foam insulation), and #17 (R-19 batt open to the basement). *(Figure 18)*

Figure 18. Proposed insulation type locations (west side)

The insulation fill configuration of the test cavities #2, #5. #14, and #17 was to have the bottom half of the cavity filled, with the same thickness of insulation installed against the inside of the rim joist. Test cavities # 8 and #11 were to be completely filled before being blocked and sealed. Planned locations for observation of temperature and moisture within the test cavities were:

1. Inside of the rim joist
2. Under the subfloor
3. Above the soffit
4. At the top quarter point of one of the side joists
5. At the bottom quarter point of one of the side joists
6. Suspended at the top quarter point in the cavity center
7. Suspended at the bottom quarter point in the cavity center

The quarter point locations were used so measurements could be taken at the side joist in the center of the insulated parts of test cavities #2, #5, #14, and #17. Similarly, one of the sensors suspended in the cavity center was centered in insulation while the other was centered in the air space open to the basement. In cavities #8 and #11, both suspended sensors will be in fully enclosed by the R-30 cavity insulation *(Figure 19)*

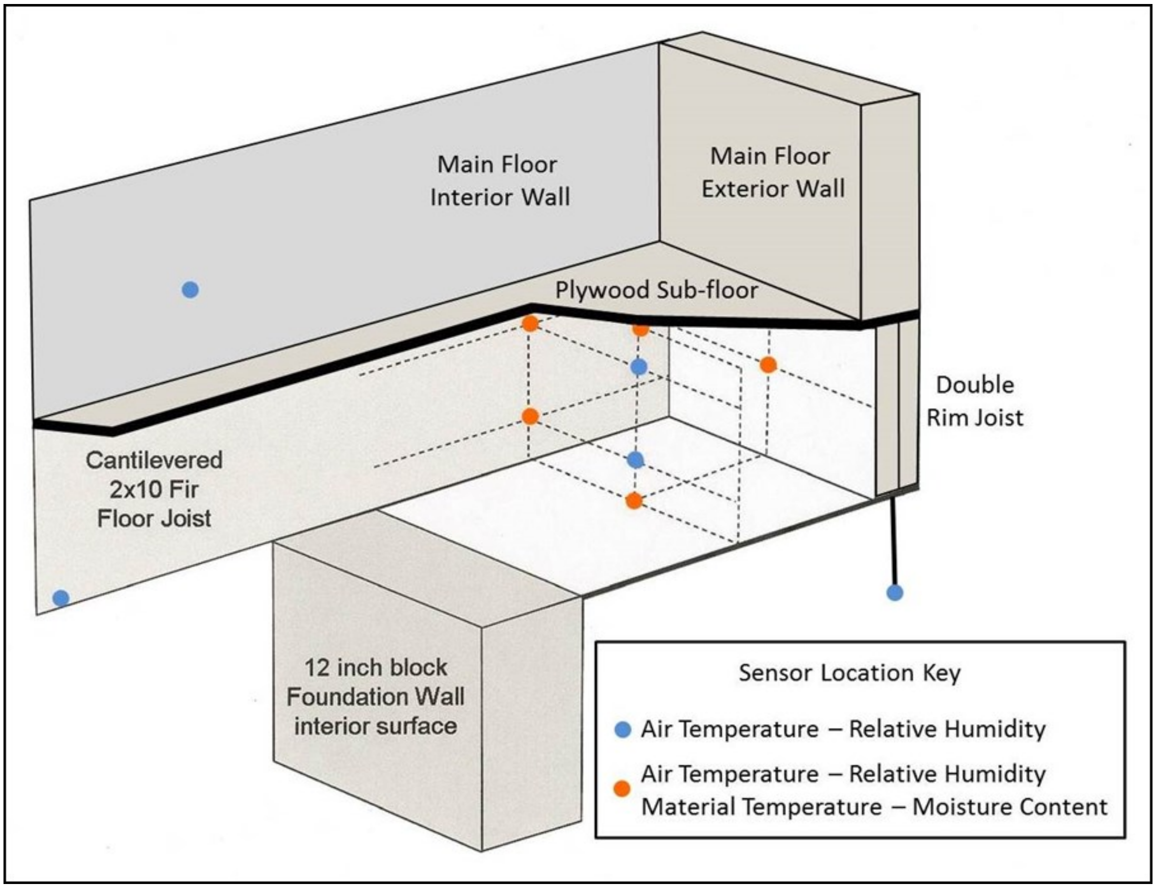


Figure 19. Proposed temperature and moisture sensor locations

Boundary condition measurements were planned for six locations, indoors and outdoors, surrounding the cantilevered floor assembly:

1. Two locations at approximate quarter points between east and west and twelve inches below the outside (north) edge of the cantilevered floor. (outdoors)
2. Two locations at approximate quarter points between east and west at the bottom of the floor joists and two feet inside of the foundation wall. (inside the basement)
3. Two locations, one inch from the interior wall between the two rooms above the cantilevered floor, six inches above the floor, and about six inches inside of the cantilever assembly. (inside the main floor rooms on the north side of the house)

Data Acquisition System Selection

Several sources for temperature and moisture monitoring components and systems were evaluated for suitability. Packaged data acquisition systems had the advantages of simplicity and compatibility but the limitations of less customization. Data acquisition systems assembled from multiple-sourced individual components had the advantage of customization but were not as simple to design and assemble or as compatible "out of the box" as the package systems.

The design required sensors that could measure air temperature, relative humidity, material temperature, and wood moisture content. Only one supplier, Lignomat USA in Portland, Oregon, was found that could provide a system package that would measure all four. Their Wireless Data Logging System includes a combination of wired and wireless components for installation in and near the test cavities. The receivers and data logger were ready to connect to the Internet service already at the test location.

The system components that would be in the test cavities seemed well suited to withstand the high temperatures generated during the installation of closed cell polyurethane foam because they were designed for use in lumber dry kilns. The package also provided storage of the data collected by the system on servers maintained by Lignomat with secure access for spot check monitoring and bulk data downloads.

Lignomat's hand-held Ligno-VersaTec moisture meter has the capability to connect to the cable connectors used in the Lignomat data acquisition system and monitor individual air temperature, relative humidity, and wood moisture content readings. The instrument can also be used to check air temperature, relative humidity, and wood moisture content using available attachments. The Lignomat system, consisting of 48 temperature/relative humidity sensors, 30 material temperature probes, 30 pairs of wood moisture content pins, 42 transmitters (156 channels), 2 receivers, mounting brackets, cables, and the Ligno-VersaTec moisture meter, were purchased and assembled to begin the bench testing process in a basement room adjacent to the cantilever floor.

A mounting bracket with a closed cell foam insulation block was fabricated for the material temperature probe and a sheet metal template *(Figure 20)* was created to mark the sensor group layout consistently in every location. A mock-up *(Figure 21)* of the planned sensor group was prepared using the template on a scrap of 1x6 pine lumber. A Tyvek enclosure *(Figure 22)* that would prevent spray-foam from damaging the sensors was designed and fabricated. Identical mounting brackets and Tyvek enclosures were used in all thirty sensor group locations to maintain uniformity at every location.

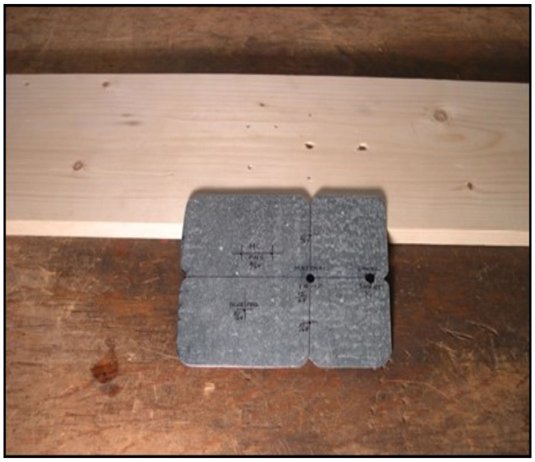


Figure 20. Sensor group template

Figure 21. Sensor group mock-up

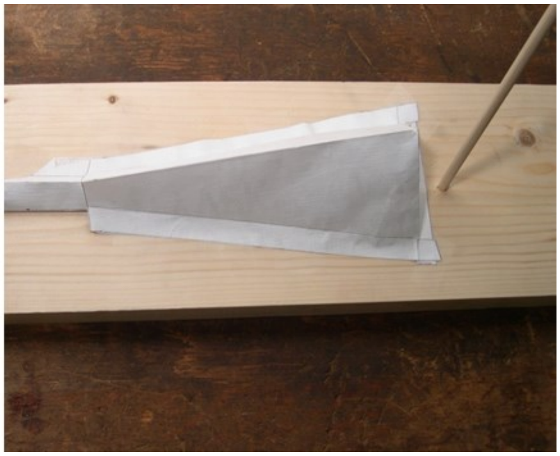


Figure 22. Tyvek enclosure over sensor group

As a precaution against losing data in case of a temporary outage of electrical power or Internet service, a back-up power system capable of maintaining power to the data logger for at least eight hours was added to the system. Two Internet lines were run to the test location to serve the data logger and a laptop used when optimizing the data logger configuration.

Preparation of the Cantilevered Floor

While the bench test of the data acquisition system was in progress, modifications were made to the existing cantilever floor to create the most uniform conditions possible from cavity to cavity. The Kraft-faced fiberglass insulation batts that were in the cantilever cavities were removed, along with the accumulated dust and dirt of forty years, from all eighteen of the accessible cavities. Several of the removed fiberglass batts had staining on the paper faces that indicated that they had experienced moisture contact over the years. A few fiberglass insulation batts had apparently served for many years as filters, collecting dust and dirt from infiltrating outside air that leaked into the house through gaps in the cantilevered floor assembly. *(Figure 23)*

Figure 23. Evidence of infiltration through the cantilever assembly

A few changes were made to the original cantilever area because of concerns about potential temperature and moisture impacts on the study. An exterior GFCI duplex outlet box and a four inch aluminum exhaust duct from the electric clothes dryer that vented to the outside through the soffit of cavity #1 were removed. About two inches of accumulated dryer lint was also removed from cavity #1. While removing the dryer vent and exterior outlet box, it was found that there was a layer of half inch fiberboard insulated sheathing between the three-eighths soffit plywood and the bottom of the cantilevered floor joists. Inclusion of this material in the cantilever soffit was not part of the planned cantilever assembly during the study and the initial reaction to this discovery was to discard the existing fiberboard sheathing and proceed as planned, but first the potential impact of this material was investigated. A 1995 NIST study comparing MOIST software to measured field conditions in exterior cavity-insulated walls showed "that the fiberboard sheathing provides additional moisture storage and reduces the peak moisture content at the inside wood surface. (Zarr, 1995, p.39) This confirmed the initial inclination to discard the existing fiberboard layer and to use only the plywood and Douglas Fir panels below the cantilevered floor joists as outlined previously in the Layout Conditions and Decisions section. Adding a moisture storage layer inside the soffit plywood did not fit the already established design for this study. The dryer was moved to another location where it could be vented to an outdoor location where it would not impact the study. A five inch warm air supply duct that was routed through cavity #9 and then up into an interior wall where it supplied heat to the room at the northwest corner of the house was removed. The openings where the duct and grill had been cut in were blocked and sealed at the bottom of the sub-floor in cantilever cavity #9 and at the surface of the wall of the main floor room above.

Before beginning removal of the original soffit plywood and fiberboard insulated sheathing, temporary blocking was installed to provide a barrier against outside weather conditions while the soffit was open. On the cavity side of a line above the inside edge of the 2x6 sill plate, three quarter inch by seven sixteenths inch closed cell foam tape *(Figure 24)* was applied against the cantilevered joist on both sides and across the top of the opening against the sub-floor plywood in each cantilever cavity. Foil faced, one inch polyisocyanurate insulation board was cut to size for each cantilever cavity and fitted snugly against the foam seal. The foam blocking was held against the foam tape by custom fitted spring wires *(Figure 25)* which allowed easy removal and replacement during modifications to the cantilever and assembly and installation of sensor groups in the cantilever cavities.

Figure 24. Temporary foam tape seal

A combination of the presence of the fiberboard sheathing and forty years' worth of corrosion on the galvanized nails used to attach the three-eighths inch soffit plywood resulted in the existing soffit plywood being completely unusable after removal. The soffit plywood and the fiberboard sheathing that were removed were in sound condition, before the effects of the nail removal process, and showed no evidence of decay. The plywood *(Figure 26)*

Figure 25. Temporary foam board blocking

and fiberboard *(Figure 27)* both showed evidence of repeated exposure to moisture. Staining was also visible on the exposed framing of the cantilever floor cavities, but did not include any evidence of decay. *(Figure 28)*

Figure 26. Moisture stains on soffit plywood

Figure 27. Moisture stains on fiberboard

The two cantilevered floor cavities over the 12 inch block foundation walls were discovered to be uninsulated on the exterior side of the 2x10 blocking that had been installed at the outside edge of the north foundation wall when the house was built in 1971. *(Figure 29)* The cantilevered floor joists were found to vary in height as much as five sixteenths of an inch. Each joist was measured and marked with the additional thickness needed to even out the cantilevered floor cavity height between sub-floor and soffit. Using clear, dry Douglas Fir 2x4's, that had been salvaged earlier when an interior

Figure 28. Exposed cantilevered floor framing

Figure 29. Wood blocking over foundation wall

basement closet had been disassembled, one and one half inch wide shim strips were produced in the thicknesses needed. While the shim strips were being ripped to size, winter arrived and the cantilever floor and a work space had to be enclosed *(Figure 30)* so they could be heated as necessary for installation progress to continue on the cantilever modifications and data acquisition system components.

Figure 30. Winter work space

After the work space was completed, two outdoor boundary condition sensor housings *(Figure 31)* were fabricated and installed between cavities 6 and 7 and between cavities 12 and 13. Two holes had been drilled a few inches vertically up into the outer 2x10 of the double rim joist and from inside cavities 7 and 12 to intersect with the vertical holes. *(Figure 32)* Cables were run through both sets of holes into the housings. The sensors were mounted in the housings, the cables were stapled in place, and closed cell foam plugs were installed at the housing end of the cable conduit and at the inside of cavities 7 and 12 to air-seal the openings. The shim strips were glued and pinned to the bottom of existing floor joists, as necessary to level the bottom face of the cantilever assembly. To provide an air-seal where the cantilever meets the exterior foundation wall and a fourth side to attach the soffit covers, 1x4 nailers were

Figure 31. Sensor and housing assembly

Figure 32. Housing and cable installed

installed in every cavity. Silicone sealant was then used to seal all joints and penetrations inside all of the cantilever cavities. One and one half inch by one quarter inch closed cell foam gasket tape was sealed to the bottom of the inner 2x10 joist in the double rim, the nailers installed along the edge of the house, and all the extended floor joists to provide an air-seal for the individual soffit covers. *(Figure 33)*

Three eighths inch plywood soffit covers were cut to fit, numbered, and installed under each of the twenty open cavities using hex-head screws. *(Figure 34)*

Figure 33. Shimmed, sealed, and gasketed

Figure 34. Plywood covers cut and fit

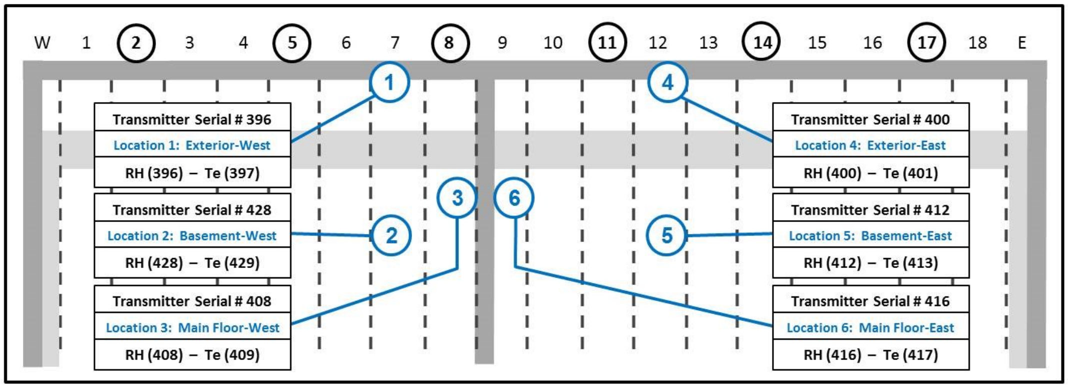
All the covers were then removed and the six Douglas Fir test panels were glued and stapled into openings cut in the center of the plywood covers for cavities #2, #5, #8, #11, #14, and #17. After the glue had fully cured, the soffit panels were all painted with two coats of exterior latex on the bottom surface that would be exposed to outdoors and on all four edges, allowing the paint to cure thoroughly after each coat.

Inside each cavity, center lines, quarter point lines, and insulation fill level lines were measured and marked out. Cavities #2, #5, #14, and #17 were marked at four and one half inches up from the joist bottom and at four and one half inches in from the rim joist to guide spray foam and R-19 batt installation. Registration marks were made on the center lines and quarter point lines to align the sensor layout template so the dowels at the quarter points were centered at nine inches in from the inside of the rim joist. Using the dowels as a starting point, the sensor groups were always located toward the inside of the house from the dowels. Identical measurements were used at each of the five locations in all six test cavities, including the Douglas Fir test panels inset in the soffit covers. Sensor groups at the side joist quarter points were laid out for installation on the west side joists of three test cavities on the west half of the cantilevered floor assembly. Sensor groups at the side joist quarter points were laid out for installation on the east side joists of three test cavities on the east half of the cantilevered floor assembly. The template was reversed from the west side to the east so that a mirror image configuration was applied to each component in each group. Holes for bracket screws, moisture pins, and support dowels for the temperature and relative humidity sensors at test cavity centers would be drilled as each group of sensors was installed.

Installing the Data Acquisition System: Cavity Components

While the cantilever assembly was undergoing modifications in preparation for the data acquisition system installation, the bench testing of the system and system components identified a few opportunities for improvement. A few parts were missing from the extension cable connectors for the material temperature probes and a number of electrical connection problems with the extension cables for the air temperature and relative humidity cables were experienced. The missing connector parts were supplied and the other cable connector problems were identified as being in the mini-stereo cable end connectors. After repeated attempts to repair the connectors, the decision was made to replace the entire custom made set with new cables that had molded-in-place cable end connectors. Every cable and connector fitting in the new set was tested using the Ligno-VersaTec meter and a temperature and relative humidity sensor from the data acquisition system and found to function reliably. The sensors and sensor groups for all forty eight locations, along with the cables and transmitters used with them in the final bench testing, were packaged as sets and assigned by cantilever cavity or boundary location.

The layout of the six boundary sensors was mapped with reference to the cantilever assembly. Sensors would measure air temperature and relative humidity at the locations shown and described on the Boundary Conditions layout map. *(Figure 35)* Relative



Layout for Boundary Conditions Sensors

Transmitter Assignment for each Blue Peg Sensor - Cavity Identification
Location of Main Floor Walls, Floor Joists, and Basement Walls

- *Blue Peg Sensors 1 and 4 are mounted outside and 12 inches below the outer (north) edge of the cantilever soffit*
- *Blue Peg Sensors 2 and 5 are mounted in the basement, 2 feet in from the cantilever cavities, and at the bottom edge of the vertical sides of the floor joists*
- *Blue Peg Sensors 3 and 6 are mounted 6 inches above the main floor and 1 inch off the east and west sides of the interior wall between the two bedrooms above the interior (south) side of the top of the cantilever cavities.*

Figure 35. Boundary Conditions layout map

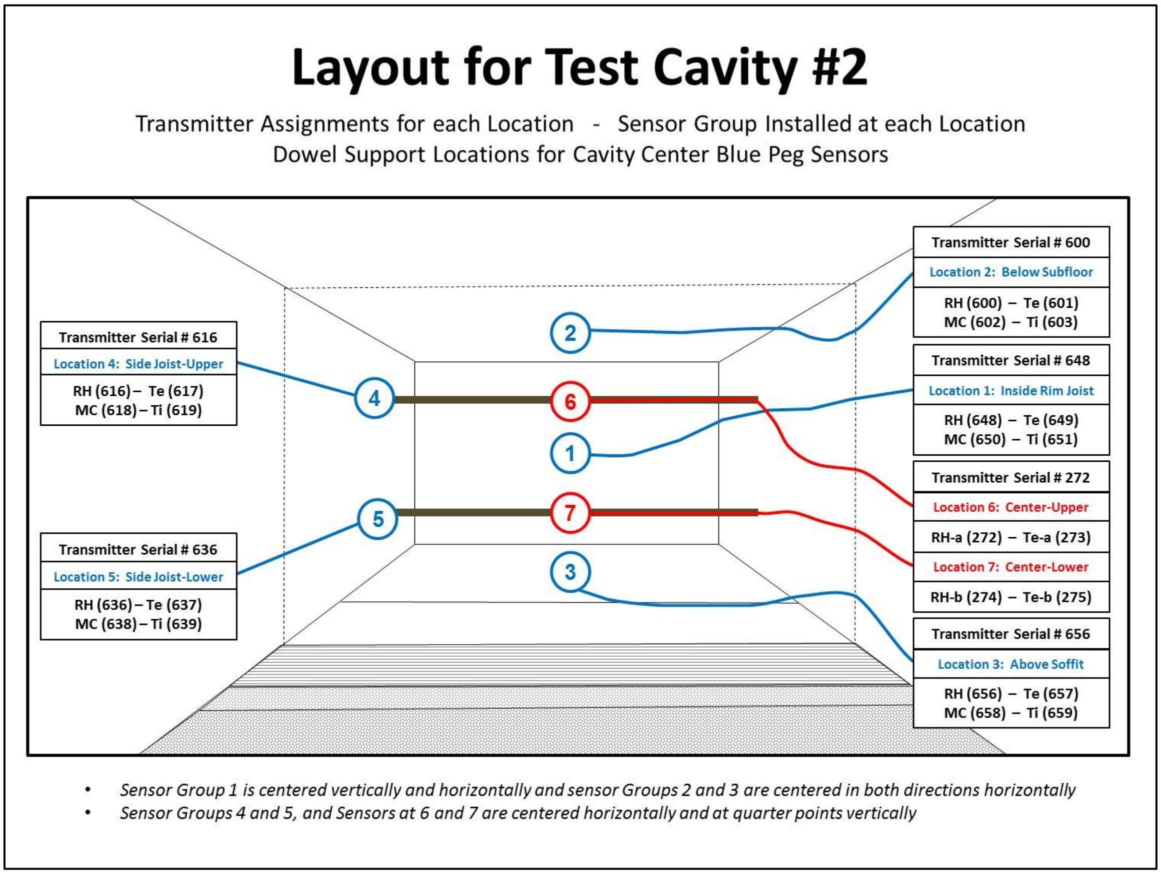
humidity (RH) and air temperature (Te) data signals will be sent from each boundary sensor through a two channel (stereo mini) cable to a one channel transmitter. The location identification system established for the six boundary sensor sets was Boundary (B) - Location # - Sensor Type, e.g., B-4-RH. The number series beginning with the transmitter serial number and listed next to each type of data point in brackets is the assigned data point number of that specific type and from that specific location when downloaded from the Lignomat server for conversion and analysis.

During the bench testing process, and continuing through the study, a separate download site was provided to monitor performance of the system by posting the most recent readings from each location as received by the Lignomat server. This allowed detection of any data reporting irregularities within the system as quickly as two hours so corrective action could be taken immediately to minimize data loss. It was this monitoring capability that allowed the identification of the cable and connector issues that were described at the beginning of this section.

The layout of each of the six test cavities was also mapped. Each test cavity has seven test locations: two air temperature-relative humidity sensors suspended in the middle of the cavities on quarter inch diameter birch dowels and five sensor groups installed on cavity surfaces as shown and described on the Test Cavity layout maps. Relative humidity (RH) and air temperature (Te) data signals will be sent from the two center-of-cavity sensors through a pair of two channel (stereo mini) cables to a two channel transmitter. Each of the five sensor groups will report relative humidity (RH), air temperature (Te), material temperature (Ti), and wood moisture content (MC). The RH-

Te data signals will be sent through a two channel (stereo mini) cable and the Ti and MC data signals will be sent through individual cables to a four channel transmitter.

The location identification system established for the twelve center-of-cavity RH-Te sensors and the thirty cavity sensor group was Cavity number - Location number - Sensor Type, e.g., 5-3-MC. As with the boundary sensors, the number series beginning with the transmitter serial number and listed next to each type of data point in brackets is the assigned data point number of that specific type and from that specific location when downloaded from the Lignomat server for conversion and analysis. The Test Cavity layout maps followed the east-west mirror image plan previously described. *(Figure 36)*


Layout for Test Cavity #2

Transmitter Assignments for each Location - Sensor Group Installed at each Location
Dowel Support Locations for Cavity Center Blue Peg Sensors

- *Sensor Group 1 is centered vertically and horizontally and sensor Groups 2 and 3 are centered in both directions horizontally*
- *Sensor Groups 4 and 5, and Sensors at 6 and 7 are centered horizontally and at quarter points vertically*

Figure 36. Sample Test Cavity layout map

At each sensor group location, following the pattern marked by the template and the example of the sensor group mock-up, pilot holes were drilled for mounting brackets, wood moisture pins, and dowels to mount the center-of-cavity RH-Te sensors. Using pre-set drill bit stops, the pilot holes for mounting brackets and the holes for the birch dowels were drilled to one quarter of an inch deep. Pre-set stops were set at one eighth of an inch deep for the moisture content pins and they were set at one quarter inch deep to the tip of the pins using a spacer block to stop the cable mounting shoulder of the pins. All sensors and cables were mounted following the Test Cavity layout map. *(Figure 37)*

Figure 37. Sensor groups and suspended sensors installed in a test cavity

After the sensor groups at the top and sides of each cavity were installed, the sensor group was installed on the Douglas Fir panel at the center of the soffit cover. *(Figure 38)*

Figure 38. Soffit cover sensor group on inset Douglas Fir panel

Tyvek cable covers were fabricated and used to mount and protect all cables inside the test cavities. The cable covers extended close enough to the sensors or sensor groups to be covered by the Tyvek sensor group enclosures. To prevent fiberglass or foam insulation from getting into any of the sensors or connectors, the edge of the cable cover toward the cavity surface was sealed down with double-sided tape so the sensor group enclosure could be sealed down to it later.

All sensors in the cavity and on the soffit cover were checked after installation to assure that sensors and cables were functioning properly. An Accurite model 00891A2 digital indoor/outdoor thermometer/hygrometer was placed next to sensor groups and allowed to stabilize before comparing the readings with those taken from the mounted temperature-relative humidity sensor and the Ligno-VersaTec handheld meter. *(Figure 39)* The temperature was taken at the surface next to each material temperature probe using a Raytek MiniTemp MT4 Infrared Laser Thermometer *(Figure 40)* and compared with readings from the server after all the sensors in the cavity were brought back online. Wood moisture content was measured using the Ligno-VersaTec handheld meter and the E14 wood moisture content pin attachment. Readings were taken in the wood one quarter inch away and parallel to the pins set at each location and then by touching the handheld pins to the top of the installed pins. *(Figure 41)* Finally, the handheld pins were held against both wires at the end of the MC cables that would be attached to the transmitter. *(Figure 42)* All readings were compared for uniformity. During the testing of installed sensors, all readings were recorded on a printed checklist form for each test cavity and a similar printed checklist form was used when testing boundary sensors.

Figure 39. Checking RH reading from sensor

Figure 40. Checking material temperature

After the sensor check for the cavity was completed and recorded, the Tyvek sensor group enclosures were installed over each sensor group using double-sided tape to seal each enclosure to the wood surface and the cable cover. In addition to the tape, all

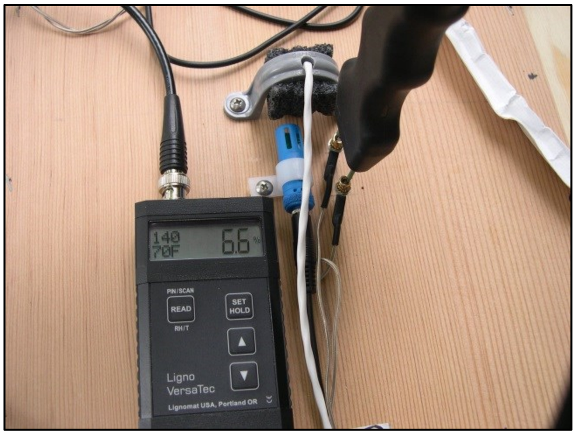


Figure 41. Checking MC at pins

Figure 42. Checking MC at cable ends

enclosures were fastened in place with three eighths inch staples. The soffit cover was then reinstalled on the bottom of the soffit cavity with just a few screws and all cables were uncoiled into the basement inside the cantilevered floor and reconnected to the transmitter used with the sensor and cable set during the bench test and brought online again. Within two to three hours, data was available for download from the Lignomat server and all sensors could be checked for proper function. After confirming that all sensors and cables were functioning properly, the remaining screws were installed to hold the soffit cover tightly against the closed cell foam gasket and the cable covers were stapled into place against the inside surfaces of the test cavity. *(Figure 43)*

Test cavities #5 and #14 were completed first so the spray applied polyurethane foam could be installed. This was done because of concerns that heat from the exothermic reaction during the foam installation might damage sensors or cables. After the foam installation was completed without damage to any sensors or cables, instrumentation was completed in the other four test cavities and at the remaining four boundary condition locations inside the house. As each test cavity was completed, cables were reconnected to transmitters and brought online.

Figure 43. Soffit cover installed. Sensor group enclosures and cable covers attached

Installing the Three Insulation Systems

The spray applied, closed cell polyurethane foam was installed first. The interior of the cantilevered floor area, ceiling and walls, and floor was masked with polyethylene sheeting and cardboard and a polyethylene sheeting temporary wall was dropped from floor to ceiling about six feet in from the cantilevered floor area. *(Figure 44)* This was to allow a safe, clean installation of the sprayed foam in a house that was occupied. During foam application, the masked off work area was depressurized by a large fan that was ducted to the outside and all proper safety precautions were observed by the professional installer from BASF *(Figure 45)*. BASF also provided the closed cell polyurethane foam materials to insulate the two test cavities and four guard cavities in the cantilevered floor.

Figure 44. Masking for foam installation

Figure 45. Foam installation

Windows and doors were opened after the installation was completed and the house was aggressively ventilated by large exhaust fans through the windows inside the masked cantilevered floor area until the off-gassing was complete. Masking, including the temporary covers placed over the sensor enclosures outside the filled areas of foamed cavities *(Figure 46),* was then removed from the cantilevered floor area

With the foam installation *(Figure 47)* and sensor and cable testing completed, installation of data acquisition components was resumed in the other four test cavities and

Figure 46. Enclosures masked outside foam fill

Figure 47. Masking removed from enclosures

at the remaining four boundary condition locations inside the house.

The four guard cavities in the R-19 sets were completed next. In each of the four cavities, one R-19 batt was cut to fit vertically against the rim joist and a second R-19 batt was cut to fit horizontally in the space between the vertical R-19 batt and the inside edge of the 2x6 sill plate over the foundation wall. The soffit cover was then removed to install the batts. Care was taken to fit the batts in the cavities with no gaps, voids, or compressions. After each R-19 guard cavity had the insulation placed from below, the soffit cover was replaced. The insulation fit was then checked from the cavity end open into the basement before starting the next cavity. When the four guard cavities had been completed, the two R-19 test cavities were insulated. In the test cavities, the batt installation process was the same except that insulation was removed from the batts to exactly fit the shape of the three sensor group enclosures and one suspended sensor enclosure that would be within the fiberglass batt filled part of the cavity. After checking the fit of each area where material was removed with an extra Tyvek enclosure, the batts were fitted into place with care taken to fit the batts in the cavities and around the Tyvek sensor group enclosures with no gaps, voids, or compressions. After each R-19 test cavity had the insulation placed from below, the cables from the soffit cover sensor group were fed through under the bottom insulation batt into the basement and the soffit cover was replaced. The insulation fit was then checked from the cavity end open into the basement so gaps, voids, or compressions still present in the fiberglass insulation after the installation of the soffit cover and cables could be fixed. All cables were labeled and fastened where they came out of the test cavities into the basement. Within two to three hours, data was available for download from the Lignomat server and all sensors could be checked for proper function after cavity completion. *(Figure 48)*

Figure 48. Completed R-19 test cavity

The insulation fill of the guard cavities with R-30 batts was completed next. Because the purchased batts did not have sufficient loft to fill the cavity to the bottom of the sub-floor at the top, a one and one half inch partial batt was cut to the same dimension as the full batt for horizontal installation in each guard cavity. The soffit cover was then removed to install the batts. In each guard cavity, batts were installed horizontally in the space between the rim joist and one inch short of the inside edge of the 2x6 sill plate over the foundation wall. Care was taken to fit the batts in the cavities with no gaps, voids, or compressions. After each R-30 guard cavity had the insulation placed from below, the soffit cover was replaced. The insulation fit was then checked from the cavity end open into the basement before starting the next cavity. When the four guard cavities had been completed, the two R-30 test cavities were insulated. In the test cavities, the batt installation process was the same except that insulation was removed from the batts to exactly fit the shape of the five sensor group enclosures and two suspended sensor enclosures that would be within the fiberglass batt filled part of the cavity. After checking the fit of each area where material was removed with an extra Tyvek enclosure, the batts were fitted into place with care taken to fit the batts in the cavities and around the Tyvek sensor group enclosures with no gaps, voids, or compressions. After each R-30 test cavity had the insulation placed from below, the cables from the soffit cover sensor group were fed through under the bottom insulation batt into the basement and the soffit cover was replaced. The insulation fit was then checked from the cavity end open into the basement so gaps, voids, or compressions that were present in the fiberglass insulation after the installation of the soffit cover and cables could be fixed. All cables were labeled and fastened where they came out of the test cavities into the basement. Within two to three hours, data was available for download from the Lignomat server and all sensors could be checked for proper function after R-30 cavity insulation had been installed. *(Figure 49)* After functionality was confirmed for all sensors in each cavity, the ends of the six cavities open into the basement were blocked. Four 4d galvanized finish nails had been set on a line marking the inside edge of the one inch, foil faced polyisocyanurate foam board blocks to hold them in place. The blocks were cut to fit snugly in place and installed against the four nails. The perimeter of each of the six blocks was then sealed to the cavity using white, 100% silicone sealant with extra care to seal around all the cables where they came out of test cavity. *(Figure 50)*

Figure 49. R-30 insulation fill completed

Figure 50. Rigid foam blocking and air-seal completed

Completing the Data Collection and Transmission System

Four boundary location sensors remained to be installed, The two in the basement were attached, just above the bottom edge, to the sides of floor joists two feet into the basement from the east side of test cavity #5 and the west side of test cavity #14. The sensors at both basement locations measure relative humidity and air temperature. Both sensor-mounting bracket assemblies are enclosed in Tyvek covers. *(Figure 51)* The two sensors on the main level are mounted one inch on either side of the interior wall between the two rooms above the cantilevered floor assembly and six inches above the floor surface. They are located above the interior (basement) end of the cantilevered floor assembly. Wire mounts were fabricated and the relative humidity-air temperature sensor-mounting bracket assemblies at each location are enclosed in Tyvek covers. *(Figure 52)*

Figure 51. Boundary sensor-basement location *Figure 52. Boundary sensor-main floor-west*

To replace the frequently changing bench test configurations, two permanent transmitter-receiver arrays were mounted on the basement wall at either side of center and just inside of the block wall window openings. All cables and transmitters had been labeled by location using the identification system described earlier. The cables were bundled and routed along the top of the foundation wall to the transmitter-receiver array that served the side of the house where they were installed. At the center of the north foundation wall, between the transmitter-receiver arrays, a small desk and shelf system was mounted on the wall to hold the data-logger, the back-up power supply for the data-logger, and a laptop computer docking station that is connected to the central Internet server-router system in the house. (Figure 53)

Figure 53. Transmitter-receiver arrays and data-logger set-up

The transmitter-receiver array on the east side is surrounded on all sides but the foundation wall by a radio frequency barrier enclosure. During the bench test process it was discovered that there was some degree of “signal crowding” at the receivers. All 42 transmitters and both receivers operate on the same radio frequency so the receivers are both trying to receive hourly signals from all 42 transmitters. By fabricating a simple type of “Faraday cage” it was possible to isolate the two halves of the system enough to realize a noticeable improvement in the amount of data getting through on the receivers. With that improvement, all parts of the data acquisition system were online and seemed to be functioning adequately to begin building the data set to be used for this study.

Chapter 4

Building the Data Set

Layout

The data set for this study was built on a Microsoft Excel spreadsheet. It was set up to receive secure data downloads from a Lignomat server which include air temperature and relative humidity values for the six boundary location sensors and twelve center-of-cavity sensors in the six test cavities. Downloads also include air temperature, relative humidity, material temperature, and wood moisture content values for the thirty sensor groups in the six test cavities. Raw data from the cantilevered floor study site is sent to the Lignomat server via the Internet connection in the test house. Downloads are received from the server over the same Internet connection.

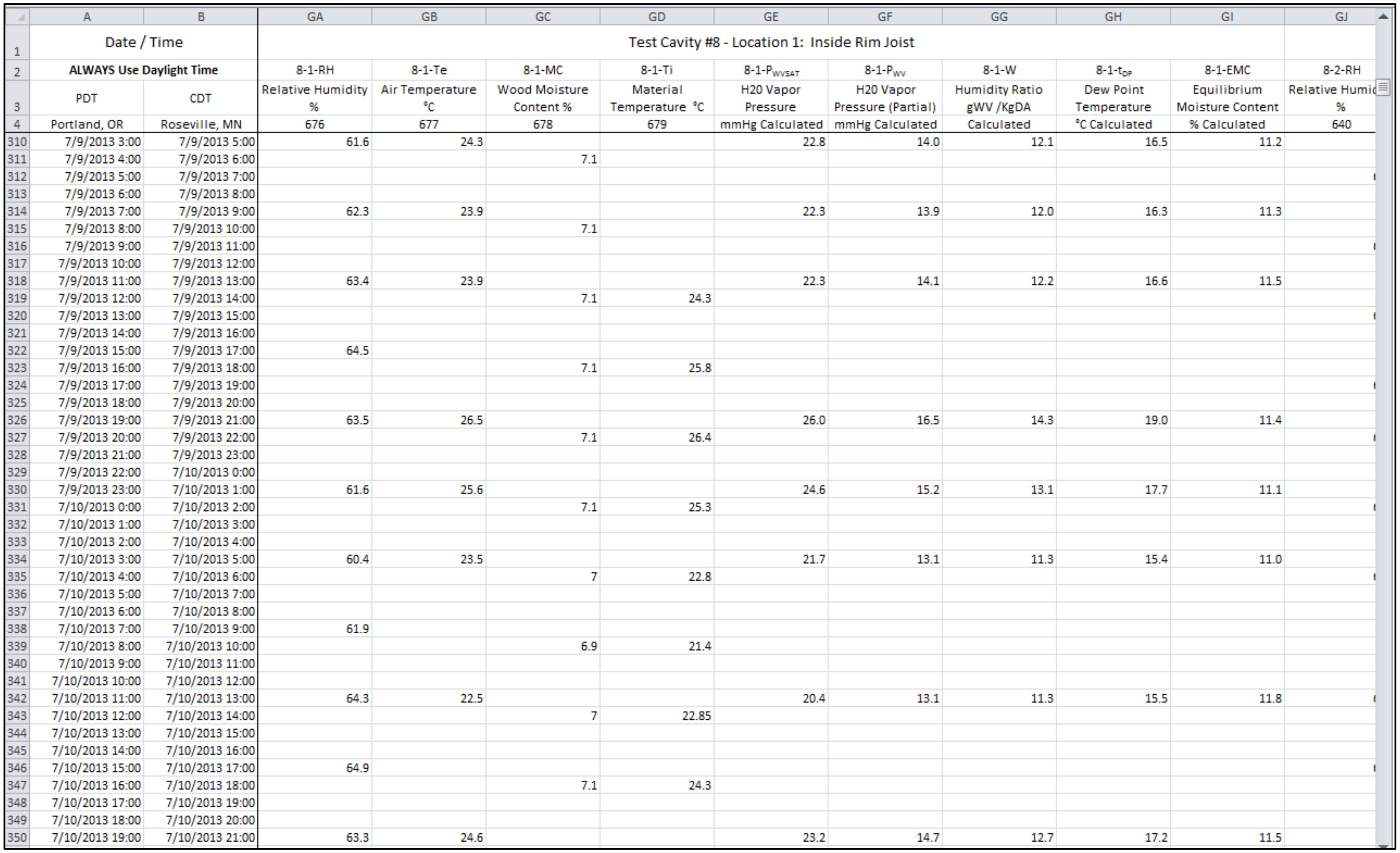
Only Daylight Time is used in the spreadsheet and in all graphic depictions of the data to maintain chronological uniformity. Each temperature, relative humidity, or moisture content reading is stored in the Lignomat server with its individual time stamp using Pacific Daylight Time. The Excel spreadsheet was set up to show both the actual Pacific Daylight Time at which each item of data was received by the server and the two hour conversion back to local time, Central Daylight Time at the test house in Roseville, Minnesota, in side-by-side columns. The data-logger has been configured to send accumulated data to the Lignomat server at one hour intervals.

In addition to the measurements taken and recorded from the study location, five more parameters were derived from the measured data by calculation and included in the spreadsheet. The data types derived by calculation were saturation vapor pressure, partial vapor pressure, humidity ratio, dew-point, and equilibrium moisture content. These parameters were selected to expand the amount of available information about conditions, driving forces, and trends in the cantilevered floor cavities and adjacent boundary locations to assist in the interpretation of the results.

In the spreadsheet header, two columns track date and time. Nine columns, four for measured data items and five for calculated items, are used to record data for each of the forty eight sensors. The set of columns for each sensor group is identified generally, at the top, by boundary or cavity location and each column contains measured values for a specific sensor or values derived by calculation. Also included in the headers is the specific identifier for each sensor or calculation, using the identification system described previously in this paper, including the server serial number used for a specific data measurement type from a specific location. *(Figure 54)*

Data

Because data downloaded from the Lignomat server and formulas used for calculation of additional parameters all use the International System of Units (SI), results are reported and discussed using SI. Randomly selected calculations were checked using the SI version of the psychrometric chart and online conversion tools to verify accuracy of the formulas used in the spreadsheet. To simplify the checking process, all formulas were set up to give results in the same units of measurement used in the SI version of the psychrometric chart. Temperatures, including dew-point, are recorded in degrees Celsius and relative humidity, wood moisture content, and equilibrium moisture content are recorded as percentages. Vapor pressures (saturation and partial) are both recorded in



	A	B	GA	GB	GC	GD	GE	GF	GG	GH	GI	GJ
1	Date / Time		Test Cavity #8 - Location 1: Inside Rim Joist									
2	ALWAYS Use Daylight Time		8-1-RH	8-1-Te	8-1-MC	8-1-Ti	8-1-P_{WVSAT}	8-1-P_{WV}	8-1-W	8-1-t_{DP}	8-1-EMC	8-2-RH
3	PDT	CDT	Relative Humidity %	Air Temperature °C	Wood Moisture Content %	Material Temperature °C	H20 Vapor Pressure	H20 Vapor Pressure (Partial)	Humidity Ratio gWV /KgDA	Dew Point Temperature	Equilibrium Moisture Content	Relative Humid %
4	Portland, OR	Roseville, MN	676	677	678	679	mmHg Calculated	mmHg Calculated	Calculated	°C Calculated	% Calculated	640
310	7/9/2013 3:00	7/9/2013 5:00	61.6	24.3			22.8	14.0	12.1	16.5	11.2	
311	7/9/2013 4:00	7/9/2013 6:00			7.1							
312	7/9/2013 5:00	7/9/2013 7:00										
313	7/9/2013 6:00	7/9/2013 8:00										
314	7/9/2013 7:00	7/9/2013 9:00	62.3	23.9			22.3	13.9	12.0	16.3	11.3	
315	7/9/2013 8:00	7/9/2013 10:00			7.1							
316	7/9/2013 9:00	7/9/2013 11:00										
317	7/9/2013 10:00	7/9/2013 12:00										
318	7/9/2013 11:00	7/9/2013 13:00	63.4	23.9			22.3	14.1	12.2	16.6	11.5	
319	7/9/2013 12:00	7/9/2013 14:00			7.1	24.3						
320	7/9/2013 13:00	7/9/2013 15:00										
321	7/9/2013 14:00	7/9/2013 16:00										
322	7/9/2013 15:00	7/9/2013 17:00	64.5									
323	7/9/2013 16:00	7/9/2013 18:00			7.1	25.8						
324	7/9/2013 17:00	7/9/2013 19:00										
325	7/9/2013 18:00	7/9/2013 20:00										
326	7/9/2013 19:00	7/9/2013 21:00	63.5	26.5			26.0	16.5	14.3	19.0	11.4	
327	7/9/2013 20:00	7/9/2013 22:00			7.1	26.4						
328	7/9/2013 21:00	7/9/2013 23:00										
329	7/9/2013 22:00	7/10/2013 0:00										
330	7/9/2013 23:00	7/10/2013 1:00	61.6	25.6			24.6	15.2	13.1	17.7	11.1	
331	7/10/2013 0:00	7/10/2013 2:00			7.1	25.3						
332	7/10/2013 1:00	7/10/2013 3:00										
333	7/10/2013 2:00	7/10/2013 4:00										
334	7/10/2013 3:00	7/10/2013 5:00	60.4	23.5			21.7	13.1	11.3	15.4	11.0	
335	7/10/2013 4:00	7/10/2013 6:00			7	22.8						
336	7/10/2013 5:00	7/10/2013 7:00										
337	7/10/2013 6:00	7/10/2013 8:00										
338	7/10/2013 7:00	7/10/2013 9:00	61.9									
339	7/10/2013 8:00	7/10/2013 10:00			6.9	21.4						
340	7/10/2013 9:00	7/10/2013 11:00										
341	7/10/2013 10:00	7/10/2013 12:00										
342	7/10/2013 11:00	7/10/2013 13:00	64.3	22.5			20.4	13.1	11.3	15.5	11.8	
343	7/10/2013 12:00	7/10/2013 14:00			7	22.85						
344	7/10/2013 13:00	7/10/2013 15:00										
345	7/10/2013 14:00	7/10/2013 16:00										
346	7/10/2013 15:00	7/10/2013 17:00	64.9									
347	7/10/2013 16:00	7/10/2013 18:00			7.1	24.3						
348	7/10/2013 17:00	7/10/2013 19:00										
349	7/10/2013 18:00	7/10/2013 20:00										
350	7/10/2013 19:00	7/10/2013 21:00	63.3	24.6			23.2	14.7	12.7	17.2	11.5	

Figure 54. Spreadsheet layout of a set of columns for one sensor group

millimeters of mercury (mmHg) and the humidity ratio is recorded in grams of water per kilogram of dry air (gWV/KgDA). To simplify the use of spreadsheet formulas across the entire data set, all nine column headings are included for each sensor location, even if all the data types are not reported from a specific location.

Formulas

The following information and equations provided the basis for spreadsheet formulas used to derive the calculated values used alongside of the measured values in the data set. The elevation at 714 Wheaton Avenue, Roseville, Minnesota test house is 945 feet or 288.036 meters above sea level. *(GIS, 2014)* The Yearly Mean Local Barometric Pressure at the test house location and elevation is calculated at 979.122hPa or 734.4039 mmHg. (Gatley, 2005, pp.131-132) *(Figure 55)*

If barometric pressure is not known for a location but altitude above or below sea level is known, then barometric pressure for the *standard atmosphere* may be calculated using the following International Civil Aviation Organization (ICAO) equation originally developed in 1925:

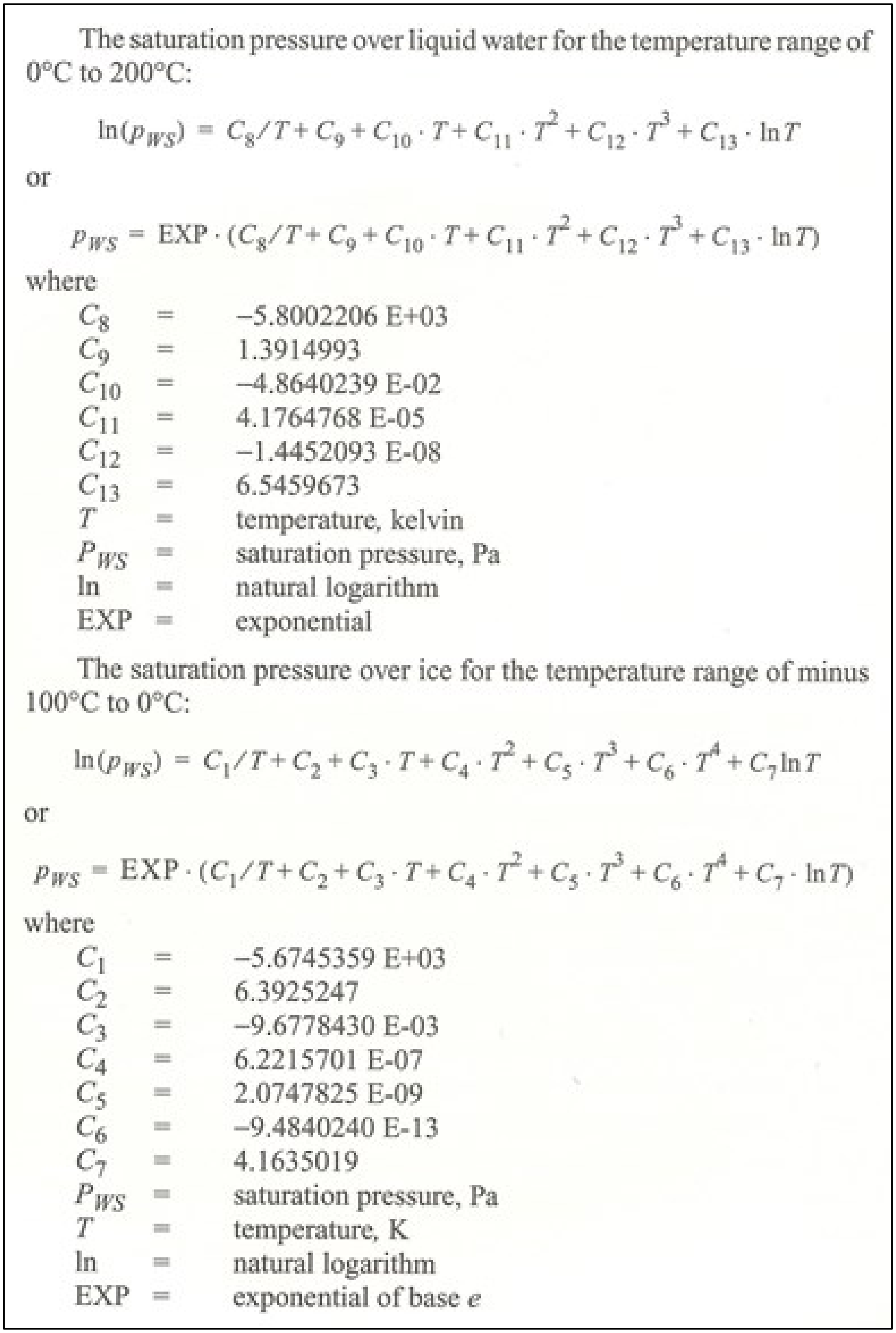
$$P_{BAR} = 101.325\,(1 - 2.25577 \cdot 10^{-5} \cdot Z)^{5.256}$$

where

P_{BAR} = yearly mean local barometric pressure at location with units of kPa
Z = altitude (elevation) above (+) or below (–) mean sea level in m

Figure 55. Yearly Mean Local Barometric Pressure equation (Gatley, 2005, pp.131-132)

The saturation vapor pressure formula was calculated using one equation for over liquid water and a second equation for over ice. (Gatley, 2005, p.26) *(Figure 56)*



The saturation pressure over liquid water for the temperature range of 0°C to 200°C:

$$\ln(p_{WS}) = C_8/T + C_9 + C_{10} \cdot T + C_{11} \cdot T^2 + C_{12} \cdot T^3 + C_{13} \cdot \ln T$$

or

$$p_{WS} = \mathrm{EXP} \cdot (C_8/T + C_9 + C_{10} \cdot T + C_{11} \cdot T^2 + C_{12} \cdot T^3 + C_{13} \cdot \ln T)$$

where

C_8 = −5.8002206 E+03
C_9 = 1.3914993
C_{10} = −4.8640239 E-02
C_{11} = 4.1764768 E-05
C_{12} = −1.4452093 E-08
C_{13} = 6.5459673
T = temperature, kelvin
P_{WS} = saturation pressure, Pa
ln = natural logarithm
EXP = exponential

The saturation pressure over ice for the temperature range of minus 100°C to 0°C:

$$\ln(p_{WS}) = C_1/T + C_2 + C_3 \cdot T + C_4 \cdot T^2 + C_5 \cdot T^3 + C_6 \cdot T^4 + C_7 \ln T$$

or

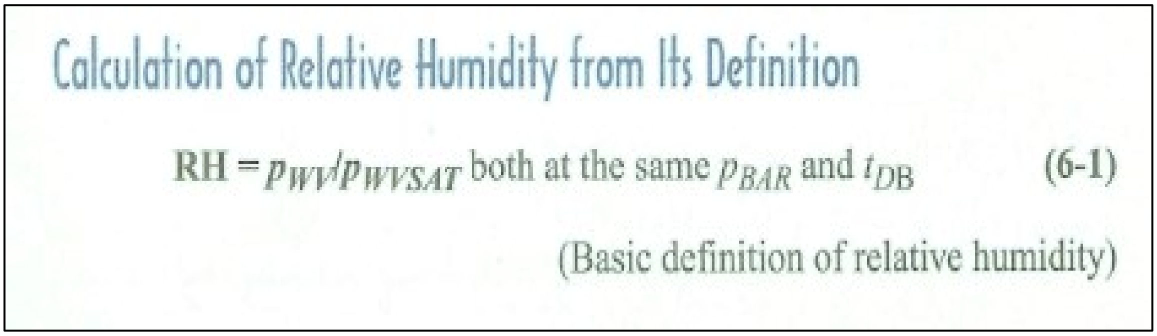
$$p_{WS} = \mathrm{EXP} \cdot (C_1/T + C_2 + C_3 \cdot T + C_4 \cdot T^2 + C_5 \cdot T^3 + C_6 \cdot T^4 + C_7 \cdot \ln T)$$

where

C_1 = −5.6745359 E+03
C_2 = 6.3925247
C_3 = −9.6778430 E-03
C_4 = 6.2215701 E-07
C_5 = 2.0747825 E-09
C_6 = −9.4840240 E-13
C_7 = 4.1635019
P_{WS} = saturation pressure, Pa
T = temperature, K
ln = natural logarithm
EXP = exponential of base e

Figure 56. Equations to derive saturation pressure (Gatley, 2005, p.26)

Partial vapor pressure is the saturation vapor pressure multiplied by relative humidity in decimal form (e.g. 50% RH = 0.5 RH) (Gatley, 2005, p.38) *(Figure 57)*



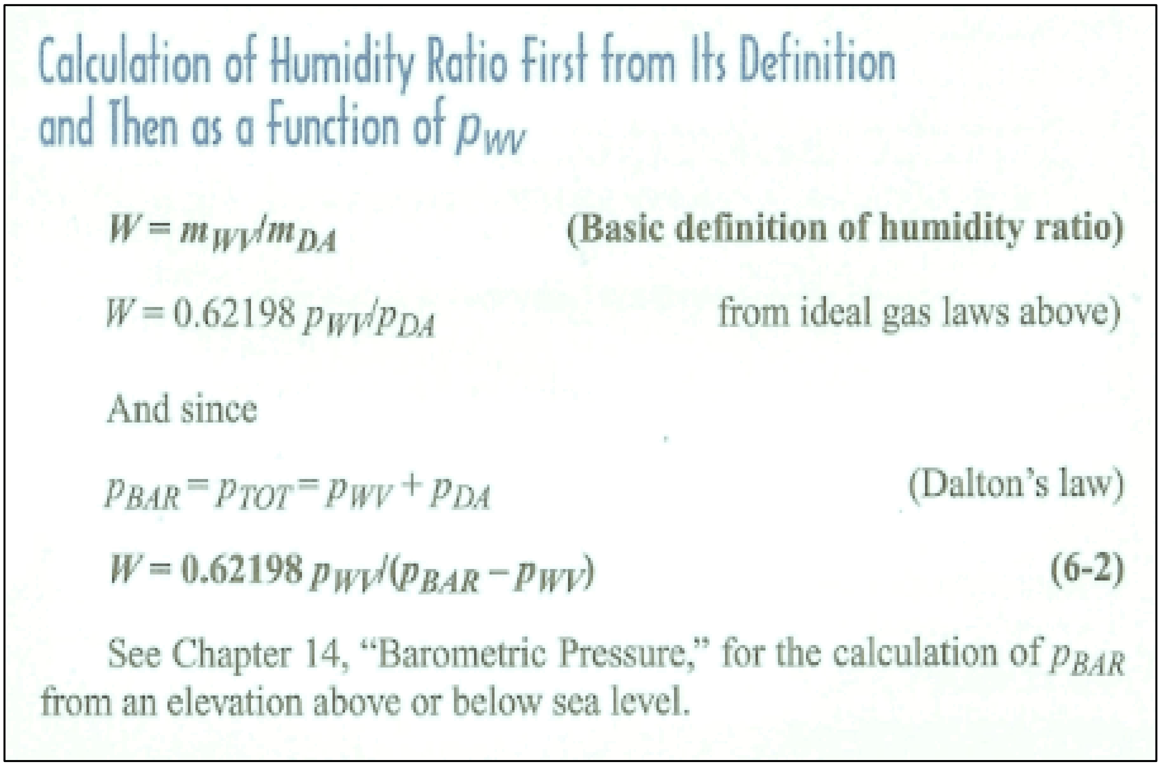
Calculation of Relative Humidity from Its Definition

$\mathrm{RH} = p_{WV}/p_{WVSAT}$ both at the same p_{BAR} and t_{DB} **(6-1)**

(Basic definition of relative humidity)

Figure 57. Equation to derive partial vapor pressure (Gatley, 2005, p.38)

Humidity ratio is the amount of water vapor relative to the amount of dry air and can be calculated by using the equations below. (Gatley, 2005, p.38) *(Figure 58)*



Calculation of Humidity Ratio First from Its Definition and Then as a Function of p_{WV}

$\boldsymbol{W = m_{WV}/m_{DA}}$ **(Basic definition of humidity ratio)**

$W = 0.62198\, p_{WV}/p_{DA}$ from ideal gas laws above)

And since

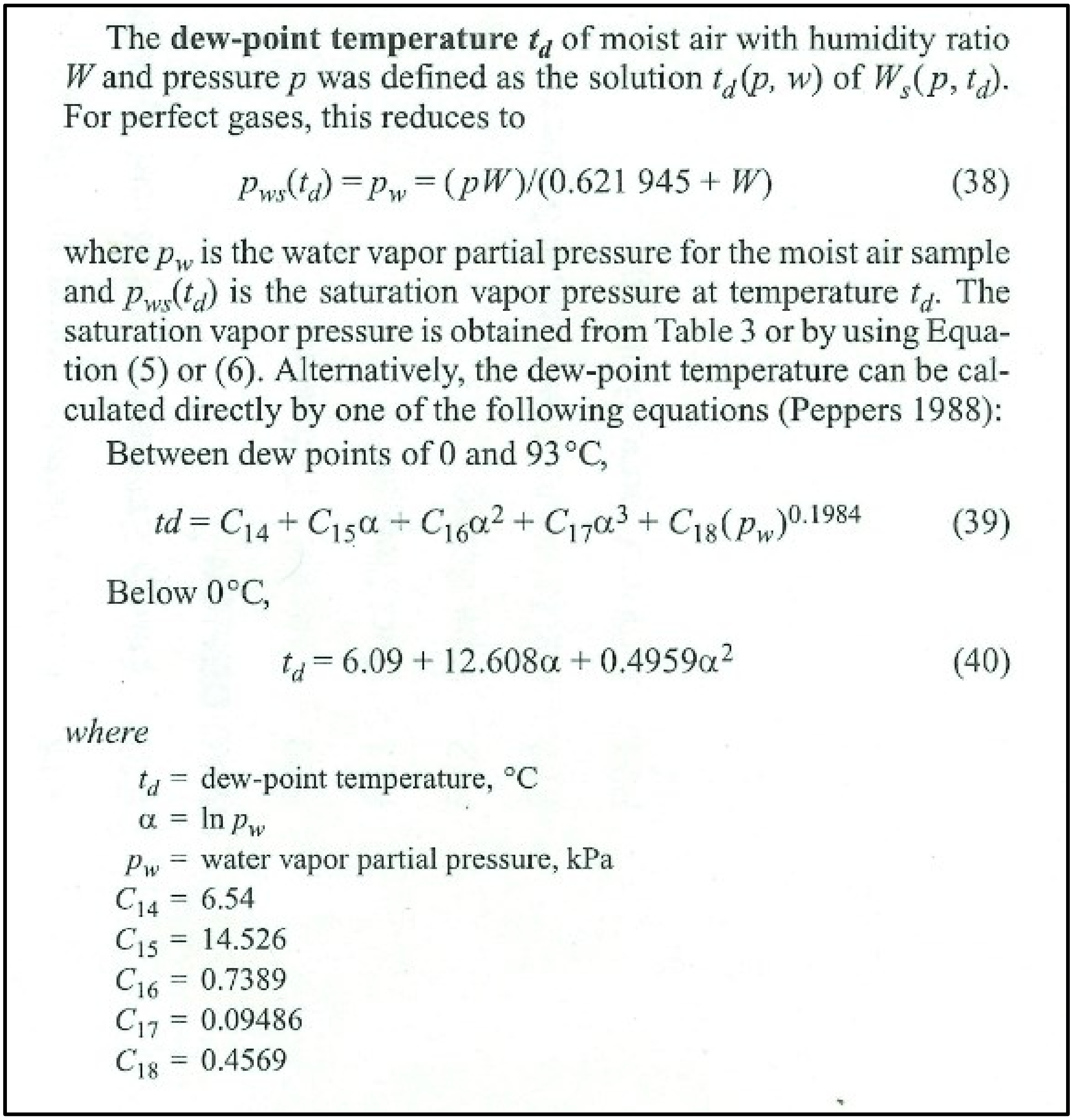
$p_{BAR} = p_{TOT} = p_{WV} + p_{DA}$ (Dalton's law)

$\boldsymbol{W = 0.62198\, p_{WV}/(p_{BAR} - p_{WV})}$ **(6-2)**

See Chapter 14, "Barometric Pressure," for the calculation of p_{BAR} from an elevation above or below sea level.

Figure 58. Equation to derive humidity ratio (Gatley, 2005, p.38)

The dew-point temperature formula was set up to be calculated using one equation for air temperatures between 0 and 93°C and a second equation for air temperatures below 0°C. (ASHRAE, 2009b, p.1.9) *(Figure 59)*



The **dew-point temperature** t_d of moist air with humidity ratio W and pressure p was defined as the solution $t_d(p, w)$ of $W_s(p, t_d)$. For perfect gases, this reduces to

$$p_{ws}(t_d) = p_w = (pW)/(0.621\,945 + W) \qquad (38)$$

where p_w is the water vapor partial pressure for the moist air sample and $p_{ws}(t_d)$ is the saturation vapor pressure at temperature t_d. The saturation vapor pressure is obtained from Table 3 or by using Equation (5) or (6). Alternatively, the dew-point temperature can be calculated directly by one of the following equations (Peppers 1988):

Between dew points of 0 and 93°C,

$$td = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}(p_w)^{0.1984} \qquad (39)$$

Below 0°C,

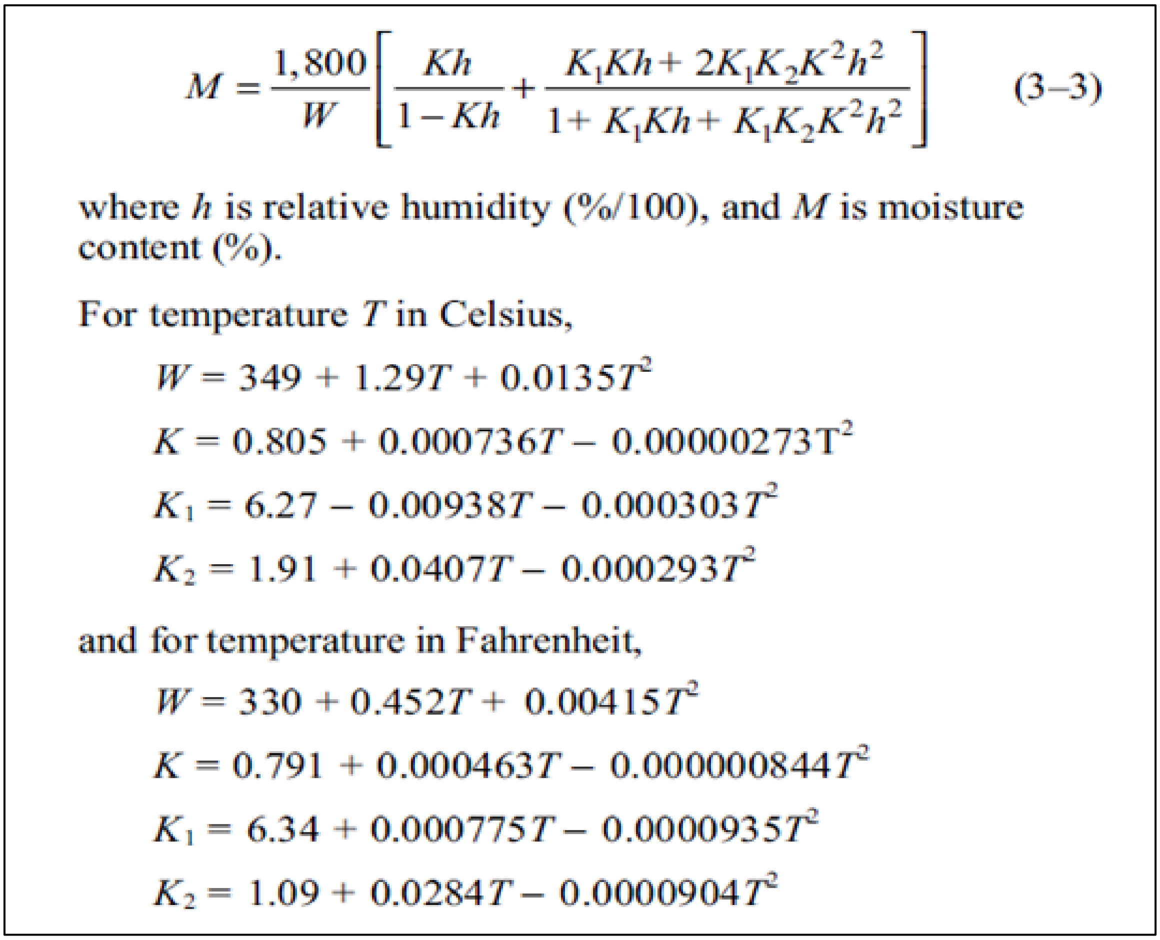
$$t_d = 6.09 + 12.608\alpha + 0.4959\alpha^2 \qquad (40)$$

where

t_d = dew-point temperature, °C
$\alpha = \ln p_w$
p_w = water vapor partial pressure, kPa
$C_{14} = 6.54$
$C_{15} = 14.526$
$C_{16} = 0.7389$
$C_{17} = 0.09486$
$C_{18} = 0.4569$

Figure 59. Equations to derive dew-point temperature (ASHRAE, 2009b, p.1.9)

"Equilibrium moisture content (EMC) is defined as that moisture content at which the wood is neither gaining nor losing moisture; an equilibrium condition has been reached. (FPL, 1999, p.3-5) *(Figure 60)*



$$M = \frac{1{,}800}{W}\left[\frac{Kh}{1-Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2}\right] \qquad (3\text{–}3)$$

where h is relative humidity (%/100), and M is moisture content (%).

For temperature T in Celsius,

$W = 349 + 1.29T + 0.0135T^2$

$K = 0.805 + 0.000736T - 0.00000273T^2$

$K_1 = 6.27 - 0.00938T - 0.000303T^2$

$K_2 = 1.91 + 0.0407T - 0.000293T^2$

and for temperature in Fahrenheit,

$W = 330 + 0.452T + 0.00415T^2$

$K = 0.791 + 0.000463T - 0.000000844T^2$

$K_1 = 6.34 + 0.000775T - 0.0000935T^2$

$K_2 = 1.09 + 0.0284T - 0.0000904T^2$

Figure 60. Equation to derive equilibrium moisture content (FPL, 1999, p.3-5)

Data Issues and Supplementary Data Sources

When the formulas had been inserted into the Excel spreadsheet and the data set populated with the calculated values, it was evident that a number of the sensors were not reporting as frequently as configured by the data-logger. This had a significant effect on the number of derived values possible where multiple measured values had to be reported for the same date and time to complete the calculation of a derived value. When graphed, however, the reduced number of values in the affected columns still provided a satisfactory image of the trends that this study was designed to identify.

A second issue was detected during the initial review of the data set which required the modification of outside boundary location air-temperature values below -15°C (5°F). The relative humidity-air temperature sensors selected for the study do not measure temperatures below -15°C. This had been overlooked during the data acquisition system selection process. During a normal winter in the Twin Cities, this issue may not have presented a problem of the same extent but the winter of 2013-2014 was not a normal winter. "The winter of 2013-14 from December - February in the Twin Cities was the coldest Meteorological Winter in 35 years. The average winter temperature in the Twin Cities was be[sic] 9.7 degrees [Fahrenheit], or nine degrees below normal. This is the coldest winter since 1978-79 which was 9.4 degrees." (MN-DNR, March 2014) Weather Underground, an online weather forecast and reporting website has a feature that allows weather data from private, home weather stations to be uploaded to and posted on their website. (KMNROSEV6, 2014) One of those private stations is three quarters of a mile north of the test house. Temperature data at the weather station is recorded and posted in five minute intervals. Except for a 15 hour gap in reporting from the Roseville weather station, it was possible to replace all of the inaccurate outside boundary condition temperatures in the data set that were below -15°C with temperatures recorded at the same time at the weather station three quarters of a mile away. Temperatures needed during the reporting gap of the Roseville station were taken from another private weather station about twice the distance to the north of the test house. (KMNVADNA4, 2014) Temperatures taken at both weather station sites at the same time as temperatures above -15°C were recorded at the test house were compared and found to be very close. This provided a workable improvement to the void in data that would otherwise exist for those very cold days.

Three other gaps in data could not be as easily remedied. The first occurred when the transmitter for location #2 in test cavity #2 failed to start when the system was brought online on June 26, 2013. No data was recorded from that location for fifteen days. A replacement transmitter was ordered and installed on July 10, 2013. The repaired original transmitter was replaced in the system on July 23, 2013. The second gap occurred when the combination relative humidity-air temperature sensor at location #3 in test cavity #14 failed on July 9, 2013. Fortunately, it could be accessed by cutting a two inch by three inch opening in the soffit cover. The sensor was checked to verify that it had failed and then replaced with a spare sensor on July 22, 2013. No data was recorded from that location for thirteen days. The third gap occurred when the Lignomat server went down on December 26, 2013. It was not restored until January 3, 2014. The data-logger had stored about two days of data which was saved when the server was returned to service. Data for the entire study was lost for a period of seven days.

During a summer storm, electrical power to the test house was lost but the back-up power source sustained electrical power to the data-logger until power was restored to the test house. There have been no other incidents that have significantly affected the data set and the system is continuing to accumulate data for future work. The data set for this study is based on measurements taken from June 26, 2013 to January 4, 2014.

Chapter 5

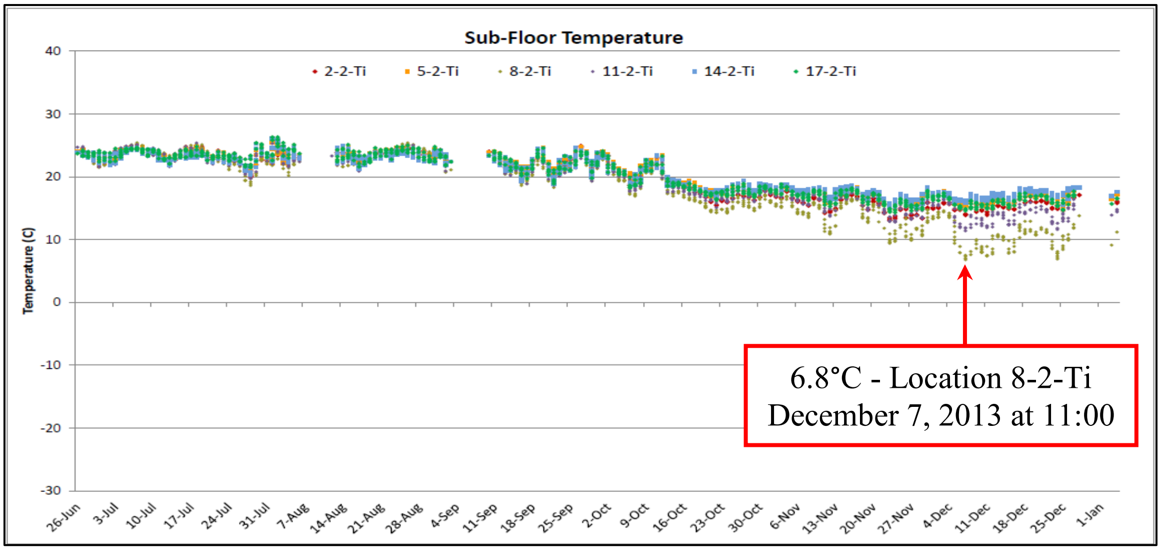
Sub-Floor Temperature above Cantilevered Floors

Results and Observations

Comfort, as experienced by feet contacting the floor surface above a cantilevered floor assembly during very cold weather, was the homeowner issue that led to this part of the study. The measurement of comfort is always challenging because each person has a different tolerance to heat or cold and their own perception of comfort. The parameter selected to compare the three insulation strategies with regard to the comfort question was the material temperature of the three quarter inch Douglas Fir sub-floor that spans the top of the cantilevered floor assembly in the test house. The two rooms on the main floor above the cantilevered floor assembly have different floor surfaces. The east room has three quarter inch oak floor over the sub-floor. The west room has wall-to-wall carpet with a pad installed on top of the three quarter inch oak floor over the sub-floor. Temperature measurements from the bottom surface of the sub-floor were recorded from all six test cavities by a uniform method to provide temperature data for a comparison of the three insulation strategies. Boundary conditions were measured outside the cantilevered floor assembly, at the floor joists inside of the cantilevered floor in the basement, and in each of the main floor rooms above the cantilevered floor.

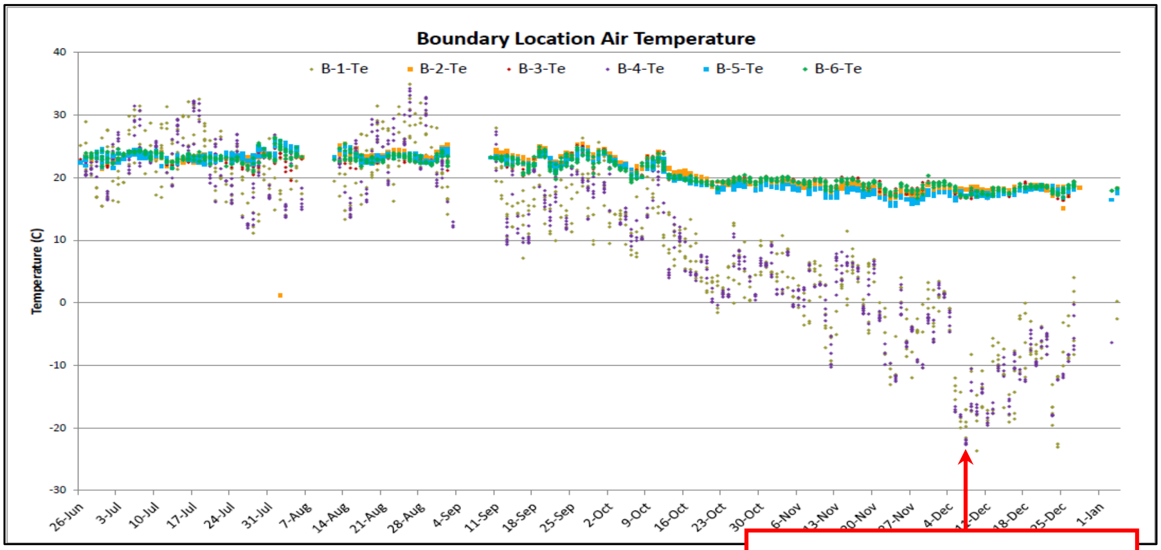
The data set includes temperature measurements at the sub-floor location in the test cavities and at the boundary locations for the time period between June 26, 2013 and January 4, 2014. The ending date was determined by the amount of time required for assembly of the data set and to conduct an analysis of the results while allowing ample time for other obligations.

The two coldest temperatures in a sub-floor location were 6.8°C, measured on December 7, 2013 at 11:00 at location 8-2-Ti and 6.9°C, measured on December 24, 2013 at 12:00 at location 8-2-Ti. *(Figure 61)*



6.8°C - Location 8-2-Ti
December 7, 2013 at 11:00

Figure 61. Sub-floor temperatures



-22.7°C - Location B-4-Te
December 7, 2013 at 6:00

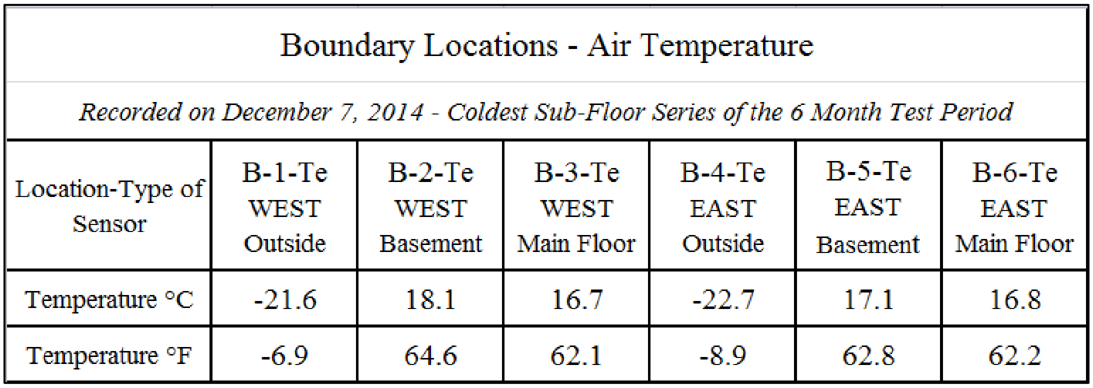
Figure 62. Boundary location temperatures

The boundary location temperature of -22.7° C, measured on December 7, 2013 at 6:00, was within one degree C. of the coldest outdoor measurement in the data set. *(Figure 62)* December 7th was selected to make the comparison because it had recorded colder temperatures both inside the test cavities and outdoors.

The relationship between the coldest outdoor temperature and the coldest floor temperature was what would be expected. Temperatures at the four boundary locations inside the house at the time were quite similar to each other. Basement temperatures at the bottom of the floor joist were 18.1°C at the west location and 17.1°C at the east location. The furnace is in the west half of the unfinished room adjacent to the cantilevered floor and might explain the warmer reading at the west location. Main floor temperatures at six inches above the floor were 16.9°C in the west room and 16.8°C in the east room. Temperatures are also given in degrees Fahrenheit in Table 1.

Table 1

Air Temperatures at boundary locations on December 7, 2013



Boundary Locations - Air Temperature

Recorded on December 7, 2014 - Coldest Sub-Floor Series of the 6 Month Test Period

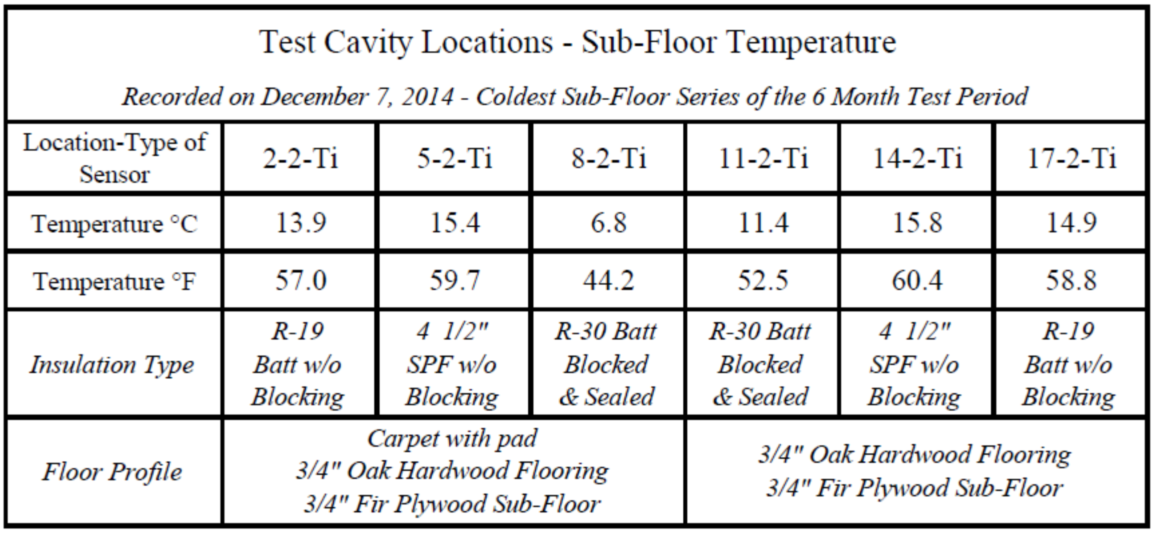
Location-Type of Sensor	B-1-Te WEST Outside	B-2-Te WEST Basement	B-3-Te WEST Main Floor	B-4-Te EAST Outside	B-5-Te EAST Basement	B-6-Te EAST Main Floor
Temperature °C	-21.6	18.1	16.7	-22.7	17.1	16.8
Temperature °F	-6.9	64.6	62.1	-8.9	62.8	62.2

The difference between the high indoor boundary temperature and the low indoor boundary temperature was only 1.4 degrees Celsius or 2.5 degrees Fahrenheit which was surprisingly similar for a day when the outdoor temperature was so much colder.

The temperatures inside the cantilevered floor cavities were not found to be so uniform. Because there were three insulation types inside the cantilevered floor assembly and two different floor coverings above the cantilevered floor assembly, some differences were expected. The measured values are shown by Table 2 for each insulation type and floor covering type combination. As proponents of leaving cantilever cavities open to the warmer basement air have asserted, the open cavities were actually warmer.

Table 2

Sub-floor temperatures for insulation and floor covering types



Test Cavity Locations - Sub-Floor Temperature

Recorded on December 7, 2014 - Coldest Sub-Floor Series of the 6 Month Test Period

Location-Type of Sensor	2-2-Ti	5-2-Ti	8-2-Ti	11-2-Ti	14-2-Ti	17-2-Ti
Temperature °C	13.9	15.4	6.8	11.4	15.8	14.9
Temperature °F	57.0	59.7	44.2	52.5	60.4	58.8
Insulation Type	*R-19 Batt w/o Blocking*	*4 1/2" SPF w/o Blocking*	*R-30 Batt Blocked & Sealed*	*R-30 Batt Blocked & Sealed*	*4 1/2" SPF w/o Blocking*	*R-19 Batt w/o Blocking*
Floor Profile	*Carpet with pad* *3/4" Oak Hardwood Flooring* *3/4" Fir Plywood Sub-Floor*			*3/4" Oak Hardwood Flooring* *3/4" Fir Plywood Sub-Floor*		

The warmest sub-floor temperatures were above the polyurethane foam cavities. Next were the sub-floor temperatures over the R-19 fiberglass batt cavities. The R-30 batt-filled and blocked and sealed cavities were significantly colder at the sub-floor. All sub-floor temperature readings were lower than the boundary conditions measured at the same time in the basement or the main floor rooms.

Differences between similar cavities under different floor coverings were more interesting. The blocked and sealed R-30 cavity under the carpeted floor was 4.6° Celsius

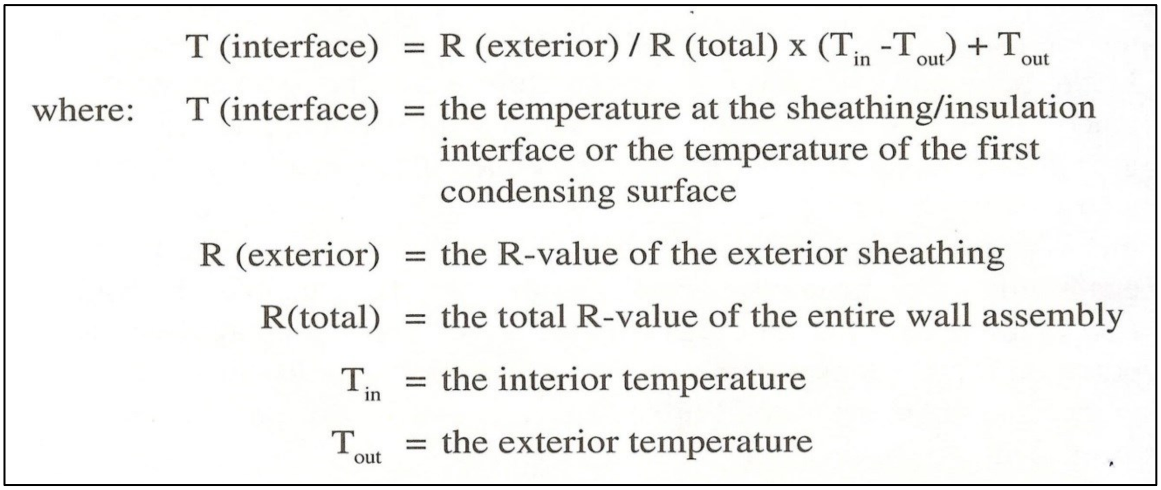
(8.3°F) colder than the blocked and sealed R-30 cavity under the bare hardwood floor. The foam insulated cavities were only measured to have a 0.4° Celsius temperature difference but the cavity under the carpeted floor was the cooler of the two. The R-19 open cavity under the carpet was 1° Celsius colder than the R-19 open cavity under the bare hardwood floor. The temperature difference between the foam cavity under the bare hardwood floor (warmest sub-floor) and the blocked and sealed R-30 cavity under the carpeted floor (coldest sub-floor) was 9 degrees Celsius (16.2 degrees Fahrenheit).

Conclusions and Recommendations

The four cavities that were open to the basement were significantly warmer than the two enclosed cavities, which would be an expected consequence of the thermal break created by the air connection to the basement. The two enclosed cavities were isolated from the basement by an R-6 panel of insulated sheathing which appeared to result in those cavities having more of a connection to outdoor conditions. Also, the blocking was air-sealed to prevent heat and moisture from moving in or out of those cavities, further isolating them from inside influence. The uniformity of interior boundary temperatures and the differences in sub-floor temperatures did not seem to be telling the whole story and raised questions about what the temperature profiles look like across the floor assembly above the six test cavities. While it was not the intent of this study to include modeling, calculation of temperature profiles for the floor was clearly necessary in an effort to provide a better understanding of the measured results.

Of most interest were floor surface temperatures in the main floor rooms above the cantilevered floor assembly. The room over the west half of the cantilever is carpeted. The room over the east half has bare hardwood flooring. A second look at temperatures of the sub-floor material at the top of test cavities also seemed to be of potential value. The data set contains air temperatures measured in the two main floor rooms and one quarter inch below the surface of the sub-floor at the top of each cantilevered floor cavity. Temperature sensors in all six test cavities are inside Tyvek sensor group enclosures so there is a small air-space inside the enclosure where the temperature readings are taken.

The equation selected to calculate the temperature profiles of the floor assemblies was one previously selected for use in a contractor workshop. An easily understood version can be found in the Builder's Guide to Cold Climates. (Lstiburek, 2004a, p.117) *(Figure 63)*



$$T\text{ (interface)} = R\text{ (exterior)} / R\text{ (total)} \times (T_{in} - T_{out}) + T_{out}$$

where: T (interface) = the temperature at the sheathing/insulation interface or the temperature of the first condensing surface

R (exterior) = the R-value of the exterior sheathing

R(total) = the total R-value of the entire wall assembly

T_{in} = the interior temperature

T_{out} = the exterior temperature

Figure 63. Temperature profile equation (Lstiburek, 2004a, p.117)

In addition to the air temperature above and below the floor, the temperature profile equation requires R-value inputs for each material used in the two different floor material profiles and R-values for the air films at the top and bottom surfaces of the floor profiles. Heat flow is downward through the floor profile in both rooms above the cantilevered floor cavities so air film R-values of 0.92 were used at the top of both floor surfaces. Air film R-values of 0.92 were also used at the bottom of the sub-floor in all six locations because temperatures are measured in the air space just off the sub-floor surface where there is no insulation in the space between the sensor and the sub-floor surface. All six location #2 (bottom of sub-floor) temperature sensors are held one fourth inch below the subfloor in the air-space created by the Tyvek sensor group enclosures attached to the bottom side of the sub-floor in each of the six test cavities. The air film R-value used for the top and bottom surfaces of the floor profiles was taken from Chapter 26, Table 1 of the ASHRAE Handbook of Fundamentals. (ASHRAE, 2009a, p.26.1)

R-values for flooring and sub-floor materials were taken from Chapter 26, Table 4 of the ASHRAE Handbook of Fundamentals. The value used for three quarter inch plywood is R-1.08. (ASHRAE, 2009a, p.26.5) The value used for three quarter inch carpet and rebounded urethane pad is R-2.38. (ASHRAE, 2009a, p.26.6) The value used for three quarter inch oak flooring is R-0.60, as calculated from the U-value per inch for oak lumber. (ASHRAE, 2009a, p.26.9)

Temperatures from the data set that were recorded on December 7, 2013 at approximately 11:00am were used in all of the temperature profile calculations for the floors above test cavities. Calculations were completed for two interface locations. First, the surface temperature of the carpet or oak flooring was calculated to be used in a comparison of floor surface temperatures above the six test cavities. Second, temperature values at the bottom surface of the plywood sub-floor were calculated to provide a comparison with the measured sub-floor material temperature values measured at the same location in each test cavity of the cantilevered floor. A table was created for each of the six test cavities to bring together the temperature values and floor assembly component R-values required for completion of the temperature profile calculations. An example of the table used for cavities under the carpeted floor (Table 3) and an example of the table used for cavities under hardwood floor (Table 4) are shown below with the input values used when calculating each temperature profile. At the bottom of each table the calculated temperature value for the main floor surface and the calculated temperature value for the bottom surface of the plywood subfloor are given. The difference between measured temperature values and calculated temperature values at the bottom surface of the sub-floor is given in the last line of the table. On December 7, 2013 at approximately 11:00am, the difference between the sub-floor temperatures of these two examples was 9 degrees Celsius (16.2 degrees F). The two cavities selected for use as examples are the cavities that reported the coldest and the warmest temperatures at the bottom surface of the sub-floor at the time of the December 7 measurements.

Measured and calculated values from the six tables created for temperature profile calculation were combined on a temperature profile table (Table 5) to compare temperatures both vertically for the temperature profile of the floor above each test cavity and horizontally to compare results between the cavities. First of all, the calculated temperature values for the bottom of the sub-floor were found to be quite close to the measured values. The least difference was -0.4 degrees Celsius and the greatest difference was -2.4 degrees Celsius, a range of only 2 degrees Celsius. These small differences appear to support the validity of the temperature profile input values and

Table 3

Values for temperature profile calculation at cavity #8

Cavity #8 - Under Carpeted Floor December 7, 2013 ~11:00am At B-1-Te, outside temperature is -21.6°C		
Insulation Type: R-30 Batt Blocked & Sealed	R-Value	Temp °C
B-3-Te - Boundary-Main Floor-West		16.7
Air Film - top of carpeted floor	0.92	
3/4 inch carpet with rebonded urethane pad	2.38	
3/4 inch Oak hardwood flooring	0.60	
3/4 inch Douglas Fir Plywood Sub-floor	1.08	
Air Film - bottom of sub-floor	0.92	
8-2-Ti - material temperature at bottom of subfloor		6.8
8-2-Te - air temperature below sub-floor		7.8
B-2-Te - Boundary-Basement-East		18.1
TOTAL R-Value	5.90	
Calculated temperature at top of carpet		15.3
Calculated temperature at bottom of sub-floor		9.2
Measured temperature compared to calculated temperature at bottom of sub-floor		-2.4

Table 4

Values for temperature profile calculation at cavity #14

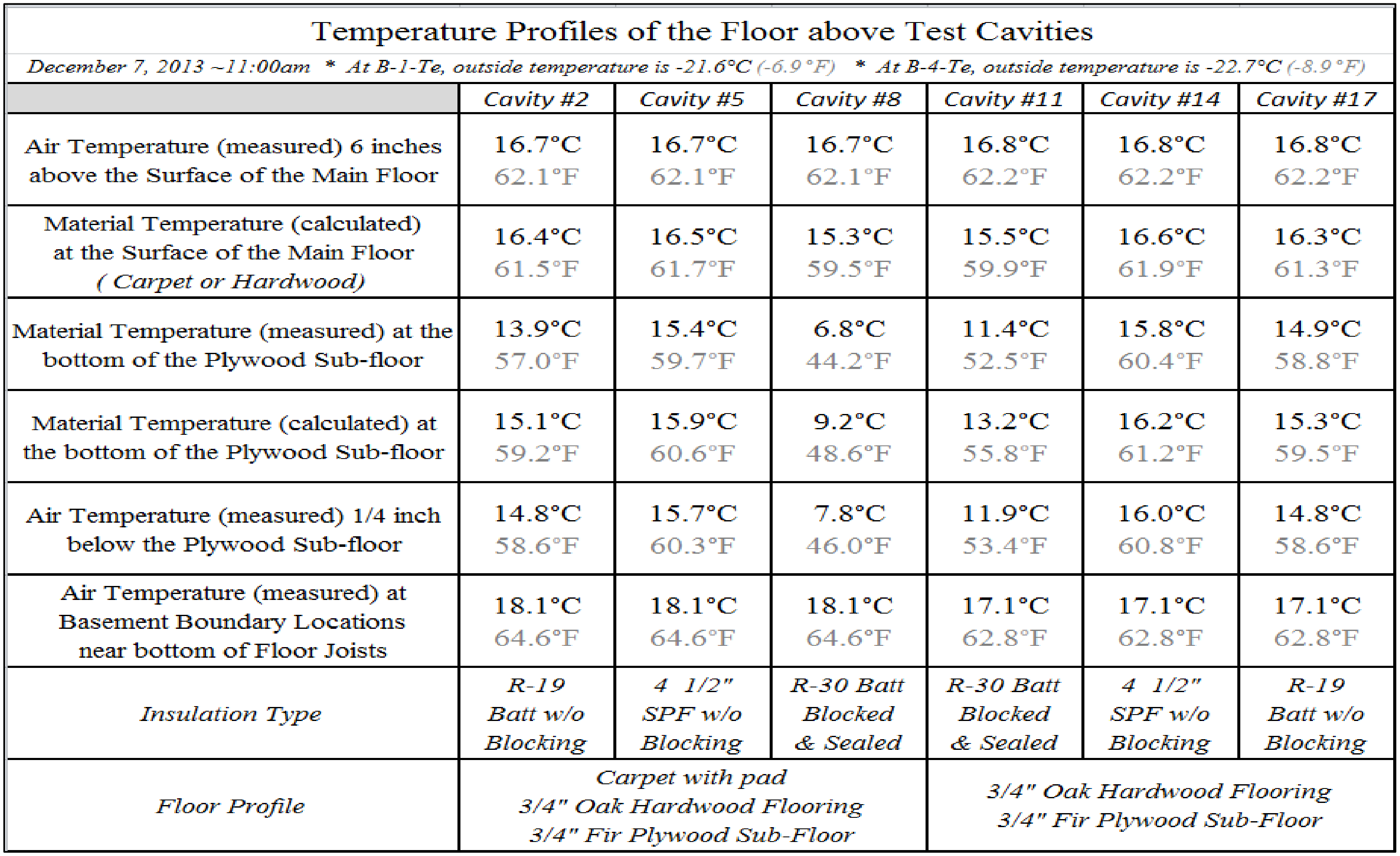
Cavity #14 - Under Hardwood Floor December 7, 2013 ~11:00am At B-4-Te, outside temperature is -22.7°C		
Insulation Type: 4 1/2" SPF w/o Blocking	R-Value	Temp °C
B-6-Te - Boundary-Main Floor-East		16.8
Air Film - top of hardwood floor	0.92	
3/4 inch Oak hardwood flooring	0.60	
3/4 inch Douglas Fir Plywood Sub-floor	1.08	
Air Film - bottom of sub-floor	0.92	
14-2-Ti - material temperature at bottom of subfloor		15.8
14-2-Te - air temperature below sub-floor		16.0
B-5-Te - Boundary-Basement-East		17.1
TOTAL R-Value	3.52	
Calculated temperature at top of hardwood floor		16.6
Calculated temperature at bottom of sub-floor		16.2
Measured temperature compared to calculated temperature at bottom of sub-floor		-0.4

calculations. As expected, the comparative temperatures across the main floor surfaces over the cantilever were somewhat reflected what was seen in the measured temperatures at the bottom of the plywood sub-floor. The main floor surface calculated temperatures over the two blocked and sealed cavities at the center of the cantilever were still the lowest, but only by 1.2 to 1.3 degrees Celsius from the warmest calculated floor temperature. The warmest calculated temperatures were over the foam insulated cavities and both were two tenths of a degree Celsius lower than the measured air temperature at six inches above the floor in the same room. The calculated floor temperatures over the two R-19 cavities were only one to three tenths of a degree colder than the calculated floor temperature over the foam cavities in the same room. All the calculated floor temperatures are in a range of 1.3 degrees Celsius (2.4 degrees Fahrenheit). These differences are similar or smaller than the differences between the measured and calculated values for the material temperatures at the bottom of the sub-floor locations.

A supplementary literature survey on the topic of thermal comfort was conducted to establish an additional basis for analysis of these calculated floor temperature findings. (Charles, 2003) (Fanger, 1977) (Linden, 2008) (Olesen, 1977) (Olesen, 1982) (Olesen, 2002) Olesen's 1977 investigation specifically addressed floor temperatures and barefooted persons. In Table 5, he lists the optimal floor temperature for a 10 minute exposure of bare feet to a carpeted floor as 24.5°C and the optimal floor temperature for a 10 minute exposure of bare feet to an oakwood floor as 26°C based on his investigation. (Olesen, 1977, p.52) This would put the floor surface temperature values calculated for this cantilevered floor study at least 7.9 °C (carpet over hardwood) and as much as 10.7°C

Table 5

Temperature profiles above test cavities



Temperature Profiles of the Floor above Test Cavities

*December 7, 2013 ~11:00am * At B-1-Te, outside temperature is -21.6°C (-6.9°F) * At B-4-Te, outside temperature is -22.7°C (-8.9°F)*

	Cavity #2	*Cavity #5*	*Cavity #8*	*Cavity #11*	*Cavity #14*	*Cavity #17*
Air Temperature (measured) 6 inches above the Surface of the Main Floor	16.7°C 62.1°F	16.7°C 62.1°F	16.7°C 62.1°F	16.8°C 62.2°F	16.8°C 62.2°F	16.8°C 62.2°F
Material Temperature (calculated) at the Surface of the Main Floor *(Carpet or Hardwood)*	16.4°C 61.5°F	16.5°C 61.7°F	15.3°C 59.5°F	15.5°C 59.9°F	16.6°C 61.9°F	16.3°C 61.3°F
Material Temperature (measured) at the bottom of the Plywood Sub-floor	13.9°C 57.0°F	15.4°C 59.7°F	6.8°C 44.2°F	11.4°C 52.5°F	15.8°C 60.4°F	14.9°C 58.8°F
Material Temperature (calculated) at the bottom of the Plywood Sub-floor	15.1°C 59.2°F	15.9°C 60.6°F	9.2°C 48.6°F	13.2°C 55.8°F	16.2°C 61.2°F	15.3°C 59.5°F
Air Temperature (measured) 1/4 inch below the Plywood Sub-floor	14.8°C 58.6°F	15.7°C 60.3°F	7.8°C 46.0°F	11.9°C 53.4°F	16.0°C 60.8°F	14.8°C 58.6°F
Air Temperature (measured) at Basement Boundary Locations near bottom of Floor Joists	18.1°C 64.6°F	18.1°C 64.6°F	18.1°C 64.6°F	17.1°C 62.8°F	17.1°C 62.8°F	17.1°C 62.8°F
Insulation Type	*R-19 Batt w/o Blocking*	*4 1/2" SPF w/o Blocking*	*R-30 Batt Blocked & Sealed*	*R-30 Batt Blocked & Sealed*	*4 1/2" SPF w/o Blocking*	*R-19 Batt w/o Blocking*
Floor Profile	*Carpet with pad 3/4" Oak Hardwood Flooring 3/4" Fir Plywood Sub-Floor*			*3/4" Oak Hardwood Flooring 3/4" Fir Plywood Sub-Floor*		

(carpet over R-30 blocked and sealed cavity) below the optimal floor temperature for bare feet found for those two floor types as determined by Olesen's investigation. This temperature difference shows all floor surfaces in this cantilevered floor study to be well below the comfort level established by Olesen's research. Since the floors are already too cold for comfort during the coldest winter temperatures outside and with the temperature differences between insulation strategies so small, it seems important to note that other factors might easily reduce the floor temperatures even further. During the preparation of the cantilevered floor assembly for this study the fiberglass insulation in every R-19 and R-30 cavity was installed with extreme care to prevent voids, gaps, and compressions. The air-sealing of every connection and penetration in every cavity in the cantilevered floor was executed at an excessive level of detail. The polyurethane foam was carefully installed by an industry professional that also trains foam insulation installers in the proper application practices for plastic foam insulations. With all this in mind, this seems a good place to repeat a comment on workmanship that was quoted much earlier in this paper.

> "Infiltration can contribute significantly to the overall heating or cooling load of a building and is directly dependent on environmental loads, envelope design and operation, and construction workmanship." (Karagiozis, 2001a)

Everything possible was done to eliminate construction workmanship variables so the results would not be influenced by factors not intended to be a part of the study.

With regard to the floor surface temperature part of this study, the worst performer of the three insulation types in the study was the R-30 cavity which was blocked and sealed, but only by a very small margin. The warm floor performance of the

R-19 cavity which is open to the basement was slightly better. The best performer judged purely on warmest floor temperature is the foam insulated cavity that is open to the basement. The amount of difference in the floor surface temperature range between the three insulation strategies examined during this study appears to be insignificant considering the results of earlier work by Olesen at the Technical University of Denmark. A reference to results of Olesen's 1975 Ph.D. thesis, *Termiske komfortkrav til gulve* (Thermal Comfort Requirements for Floors) reports the finding that "At floor temperatures below 20-22°C the percentage of people experiencing cold feet increases rapidly. (Fanger, 1977, p. 289)

Since all floor surface temperatures measured during the coldest day of this cantilever floor investigation are much colder than optimal temperatures and there is so little difference in the temperatures measured over the different cantilever insulation types, it may be that future work should be more directed toward developing improved methods of managing heat loss through cantilever floor assemblies and keeping floor surfaces at optimal temperatures for thermal comfort.

Chapter 6

Moisture Behavior in Cantilevered Floor Cavities

Results and Observations

Long term durability of the house depends on selecting building assemblies and building processes that minimize risk. Moisture content of wood was measured at five locations in each of the six cantilevered floor test cavities to identify potential risks by location and insulation strategy. The same data set is used for the moisture behavior evaluation as was used for the floor temperature evaluation. It contains all test cavity and boundary location measurements and calculated data for the time period between June 26, 2013 and January 4, 2014.

Before evaluating the data, it is important to know where that potential for risk begins. "Serious decay occurs only when the moisture content of the wood is above the fiber saturation point (average 30%). Readings of moisture content over 20 % are considered to indicate danger of decay [.]" (Sherwood, 1994, p.80) It is equally important to know when the readings are within acceptable limits. The USDA Forest Products Laboratory recommends a wood moisture content between six and ten percent for woods used as interior woodwork, flooring, and trim and a wood moisture content between nine and fourteen percent for wood used as exterior siding, trim, framing and sheathing. (FPL, 1973, p.4) Based on these cautions and recommendations, wood moisture content measurements at or below fourteen percent in the data will be considered within acceptable limits. Wood moisture content measurements that trend above fourteen percent in graphic representations of the data will raise concern and values still trending upward toward twenty percent wood moisture content will be considered to indicate a potential durability risk. In addition to wood moisture content, dew-point temperature, material temperature, and equilibrium moisture content were also graphed for each of the thirty sensor group locations. This allows the data for wood moisture content to be viewed with data indicative of condensation and wetting potential. If the material temperature drops below the dew-point temperature for the same time, it indicates a high probability of moisture vapor condensing on the colder material surface. The equilibrium moisture content serves as an indicator of wetting or drying potentials that could impact measured wood moisture content.

To give added perspective, five sets of graphs were produced to provide comparisons of relative humidity (Figures 64-66), air temperature, vapor pressure, partial vapor pressure, and humidity ratio. Each of the five data type sets includes eight graphs. In each set, one graph compares values from all six boundary locations. Values of each data type for the five sensor groups and two suspended sensors in each of the six test cavities are graphed on the other seven pages of each set.

A review of the first set of thirty graphs identified ten locations where values for wood moisture content or equilibrium moisture content moved above fourteen percent. All ten locations were at the inside of a rim joist (location #1) or at the inside of a soffit (location #3). (Figures 67-72) Based on that outcome, Table 6 was created to compare and illustrate the wood moisture content percentage, the equilibrium moisture content percentage, and the relative humidity percentage. Table 6 also notes any wetting trend indicated by the graph for each location. Although locations 5-1 and 14-1, both at the rim joist location in foam insulated cavities, did not report values over fourteen percent, they are included in the table. To differentiate between levels of concern, MC values over fourteen percent, EMC values over twenty percent, RH values over ninety three percent, and increasing wetting trends are highlighted as causing active concern about durability. EMC values more than fourteen percent and less than twenty percent, RH values more than eighty five percent and less than ninety three percent, and slightly increasing wetting trends are highlighted as having the potential to cause concern about durability.

Table 6

Moisture behavior in test cavities

Wood Moisture Content - Equilibrium Moisture Content - Relative Humidity - Wetting Trend					
June 26, 2013 to January 4, 2014		Highest Value Recorded			
Location	Insulation Type	%MC	%EMC	%RH	Wetting Trend
2-1 Inside Rim Joist	R-19 - Open	10.4	22.0	92.0	Slight Increase
2-3 Above Soffit	R-19 - Open	16.3	25.1	95.9	Increasing
5-1 Inside Rim Joist	Foam - Open	5.9	12.3	64.8	No Increase
5-3 Above Soffit	Foam - Open	10.9	15.1	77.6	Slight Increase
8-1 Inside Rim Joist	R-30 - Blocked	9.3	15.1	76.1	Slight Increase
8-3 Above Soffit	R-30 - Blocked	10.9	17.9	85.4	Slight Increase
11-1 Inside Rim Joist	R-30 - Blocked	8.6	15.5	78.7	Slight Increase
11-3 Above Soffit	R-30 - Blocked	11.4	19.0	87.3	Slight Increase
14-1 Inside Rim Joist	Foam - Open	6.4	11.5	60.8	No Increase
14-3 Above Soffit	Foam - Open	10.8	14.9	75.1	Slight Increase
17-1 Inside Rim Joist	R-19 - Open	9.7	20.5	88.8	Slight Increase
17-3 Above Soffit	R-19 - Open	19.6	25.5	96.4	Increasing
No Concern about Durability		Potential Concern about Durability		Active Concern about Durability	

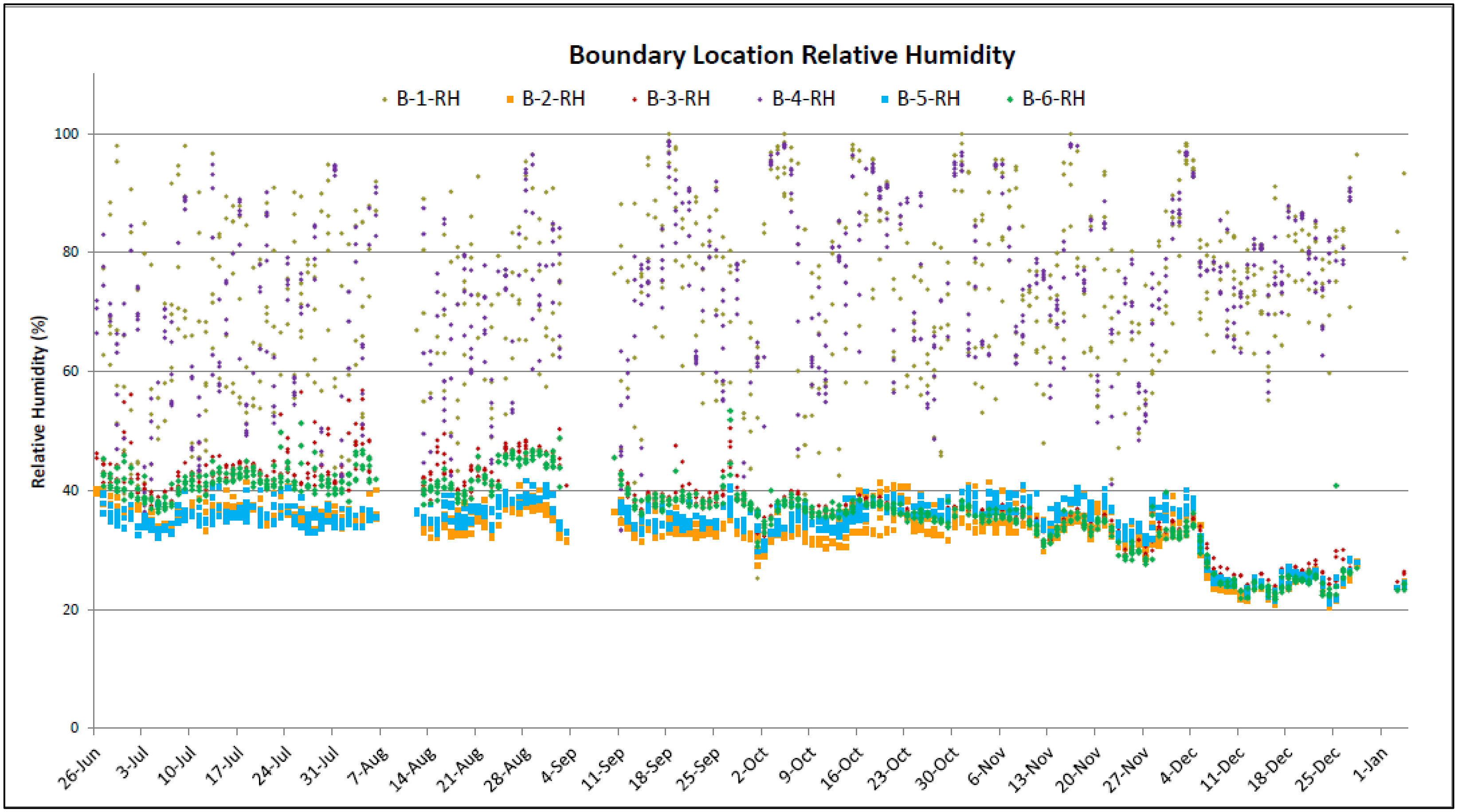


Figure 64. Relative humidity – Boundary locations

B-1-RH	**B-2-RH**	**B-3-RH**	**B-4-RH**	**B-5-RH**	**B-6-RH**
Outside	**Basement**	**Main Floor**	**Outside**	**Basement**	**Main Floor**
WEST	**WEST**	**WEST**	**EAST**	**EAST**	**EAST**

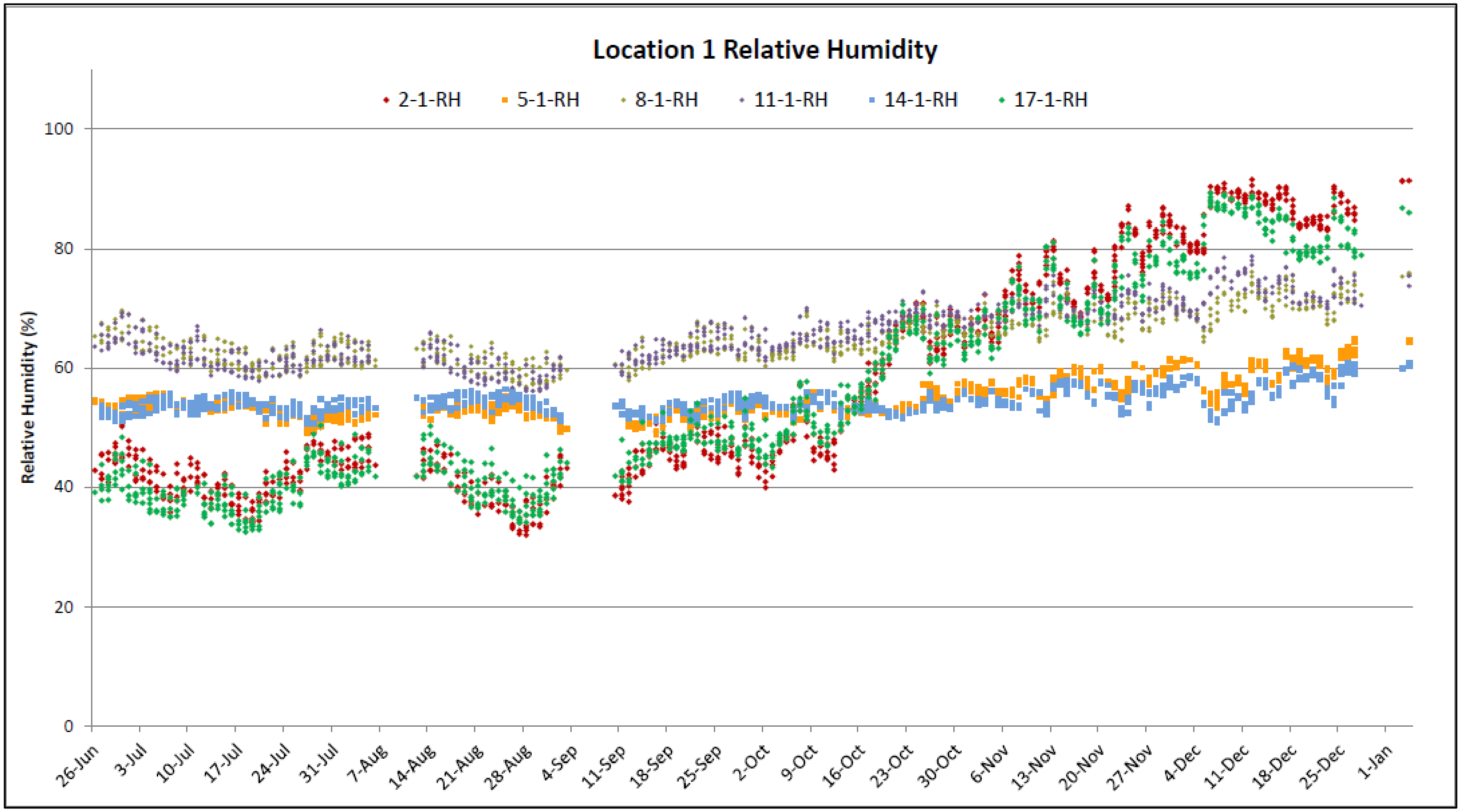


Figure 65. Relative humidity inside rim joist – Test cavities

2-1-RH	**5-1-RH**	**8-1-RH**	**11-1-RH**	**14-1-RH**	**17-1-RH**
RIM	**RIM**	**RIM**	**RIM**	**RIM**	**RIM**
R-19 Open	**FOAM Open**	**R-30 Blocked**	**R-30 Blocked**	**FOAM Open**	**R-19 Open**

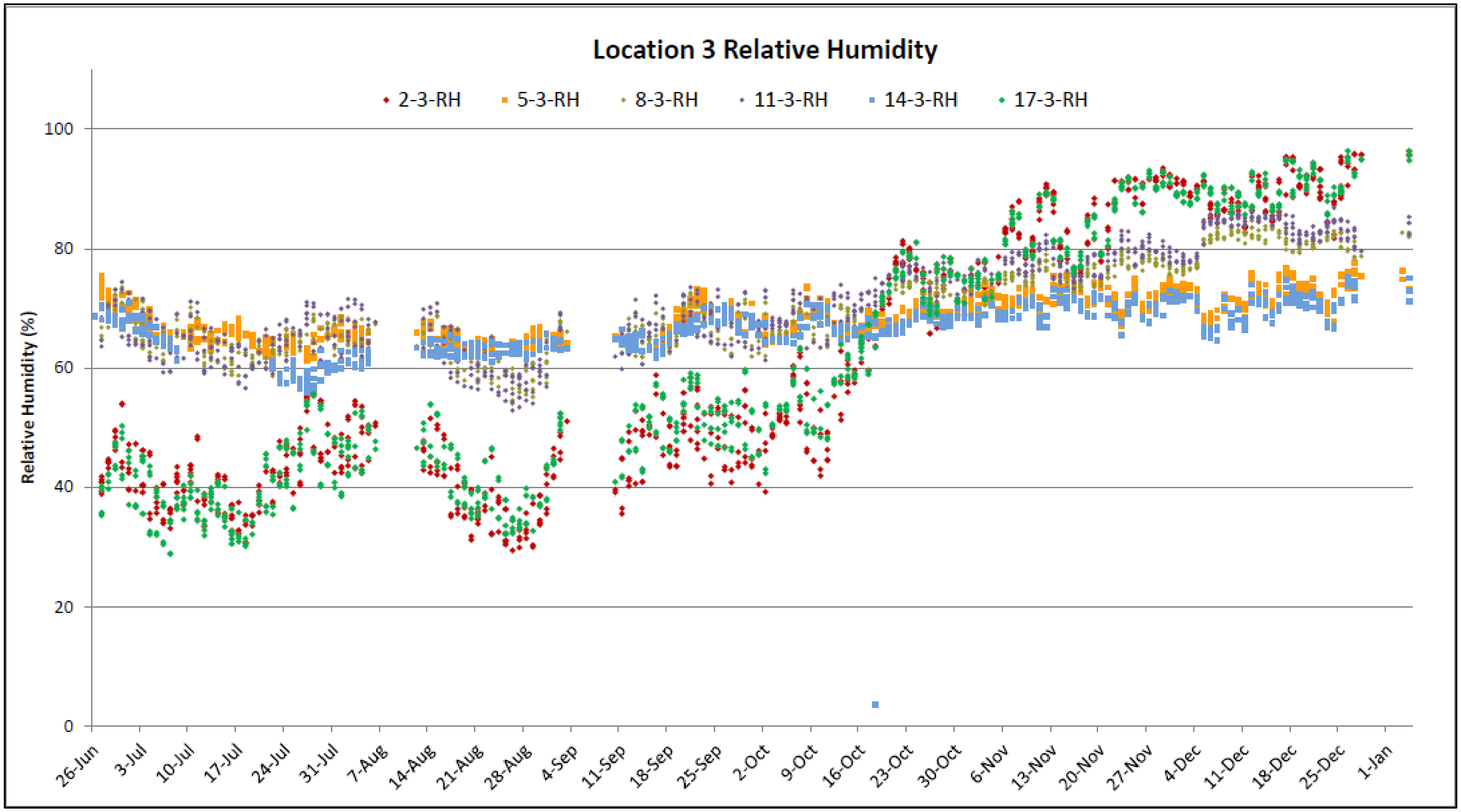


Figure 66. Relative humidity above soffit – Test cavities

2-3-RH **SOFFIT** **R-19 Open**	**5-3-RH** **SOFFIT** **FOAM Open**	**8-3-RH** **SOFFIT** **R-30 Blocked**	**11-3-RH** **SOFFIT** **R-30 Blocked**	**14-3-RH** **SOFFIT** **FOAM Open**	**17-3-RH** **SOFFIT** **R-19 Open**

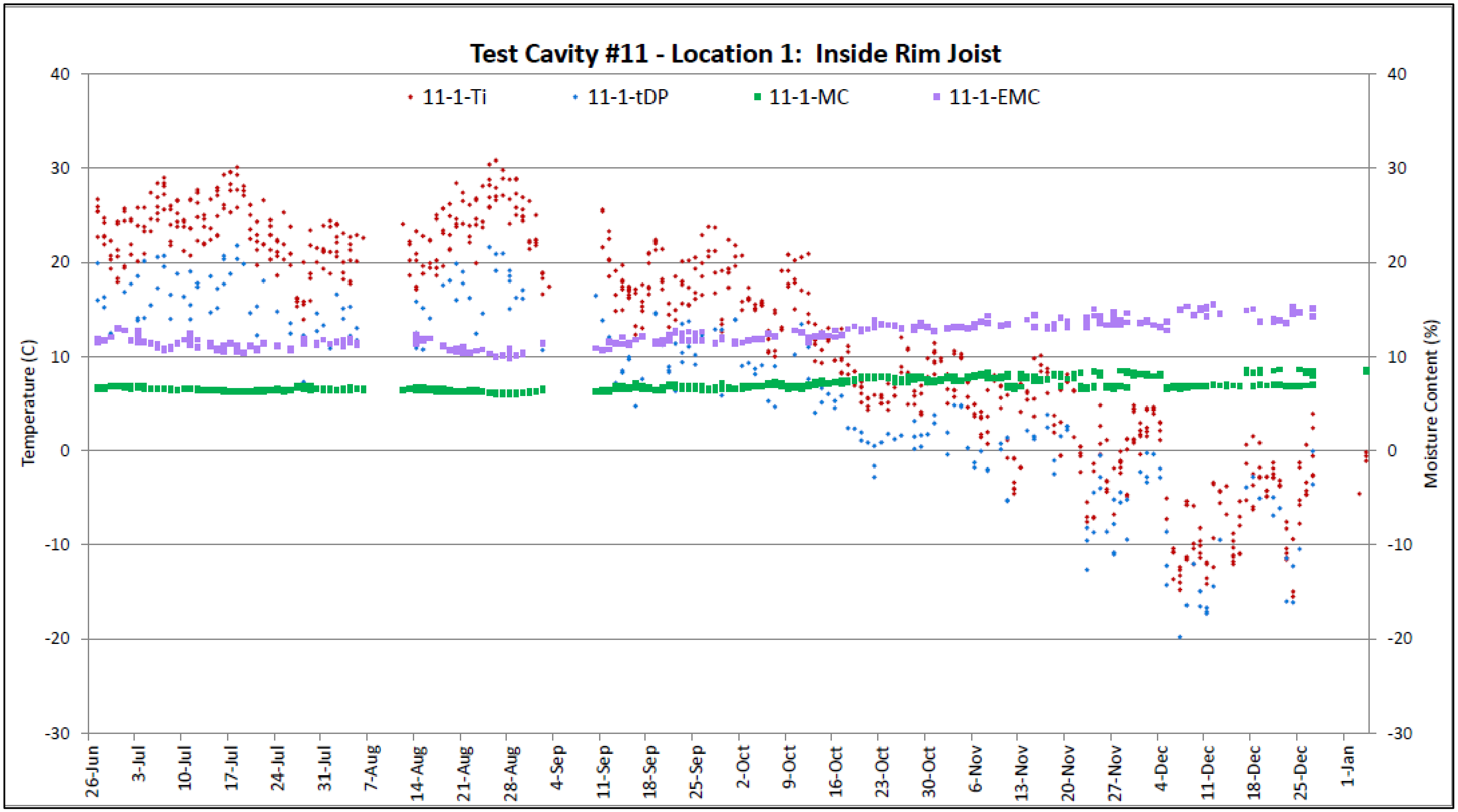


Figure 67. Moisture behavior inside rim joist – Blocked and sealed R-30 test cavity

Rim Joist Surface Temperature

Dew Point Temperature

Wood Moisture Content

Equilibrium Moisture Content

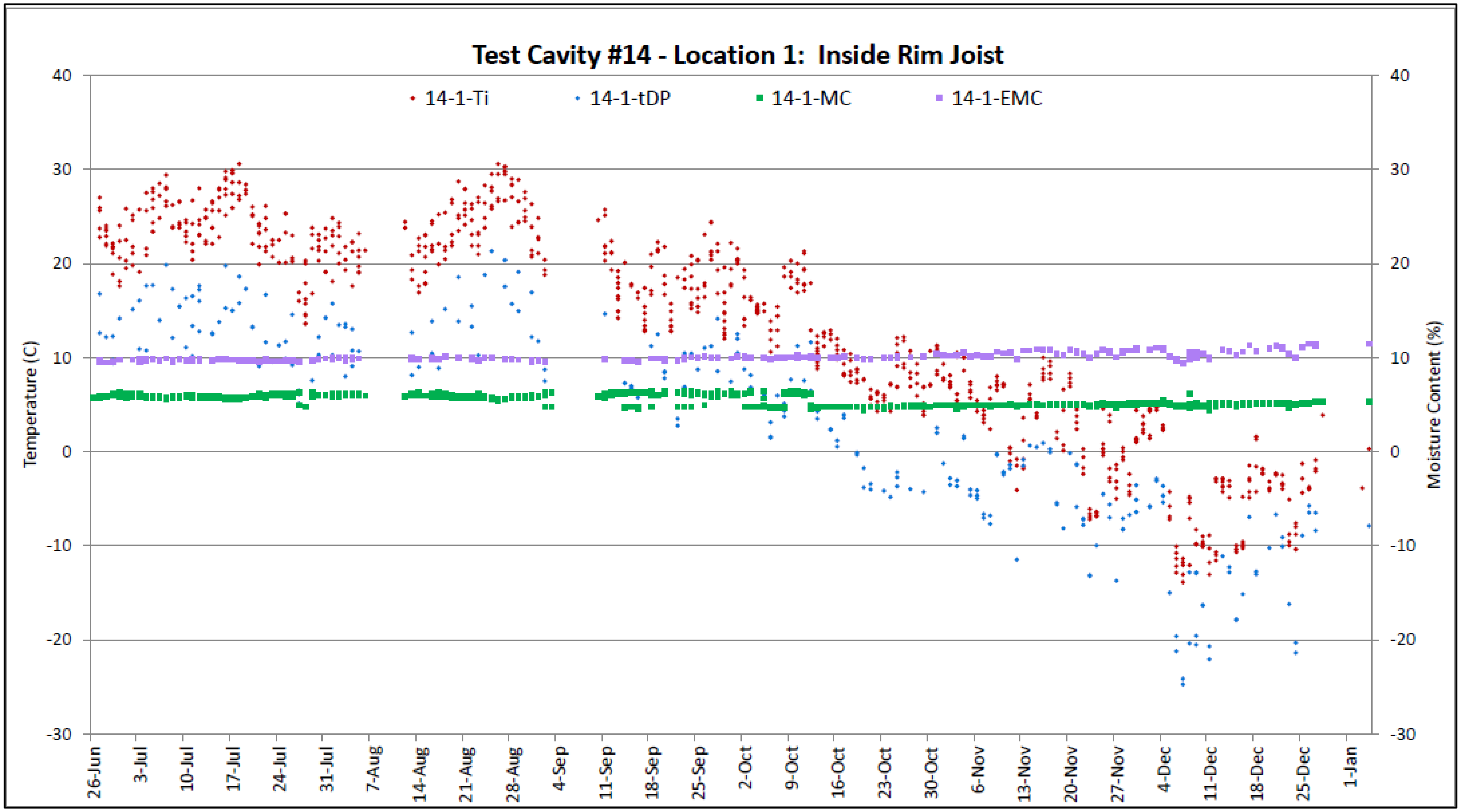


Figure 68. Moisture behavior inside rim joist – Spray foam insulation test cavity

Rim Joist Surface Temperature

Dew Point Temperature

Wood Moisture Content

Equilibrium Moisture Content

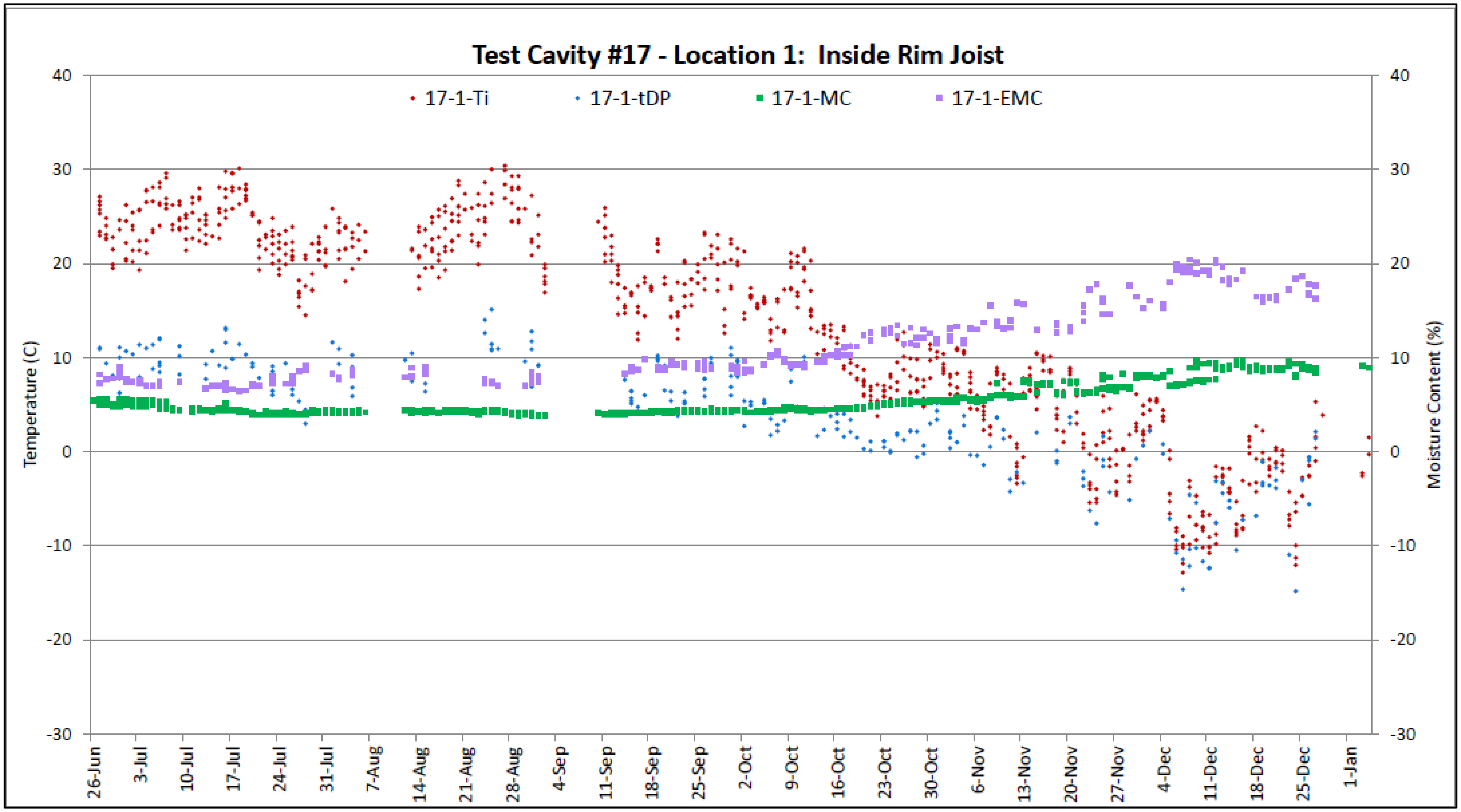


Figure 69. Moisture behavior inside rim joist – Open R-19 batt test cavity

Rim Joist Surface Temperature

Dew Point Temperature

Wood Moisture Content

Equilibrium Moisture Content

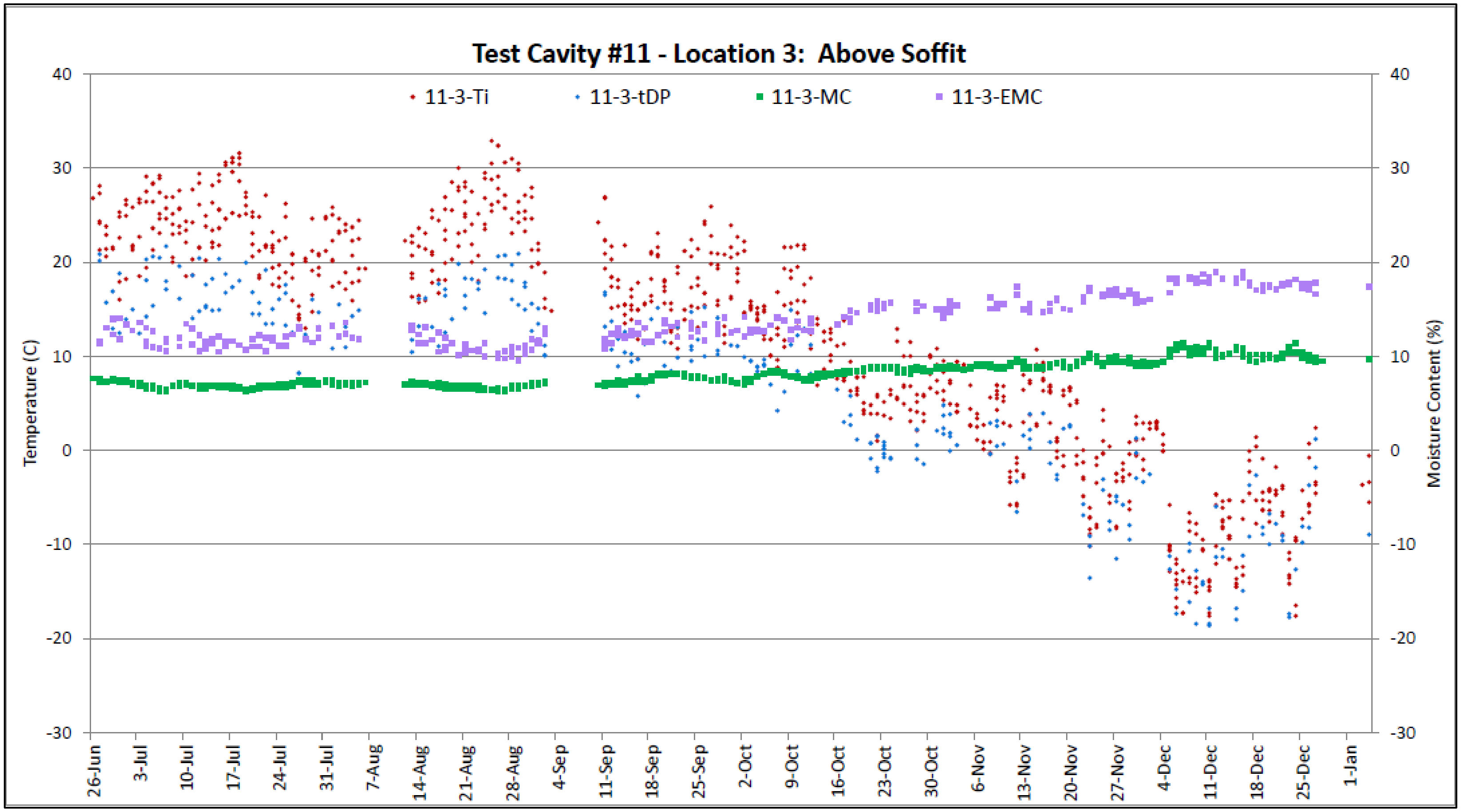


Figure 70. Moisture behavior above soffit – Blocked and sealed R-30 test cavity

Inside Soffit
Surface
Temperature

Dew
Point
Temperature

Wood
Moisture
Content

Equilibrium
Moisture
Content

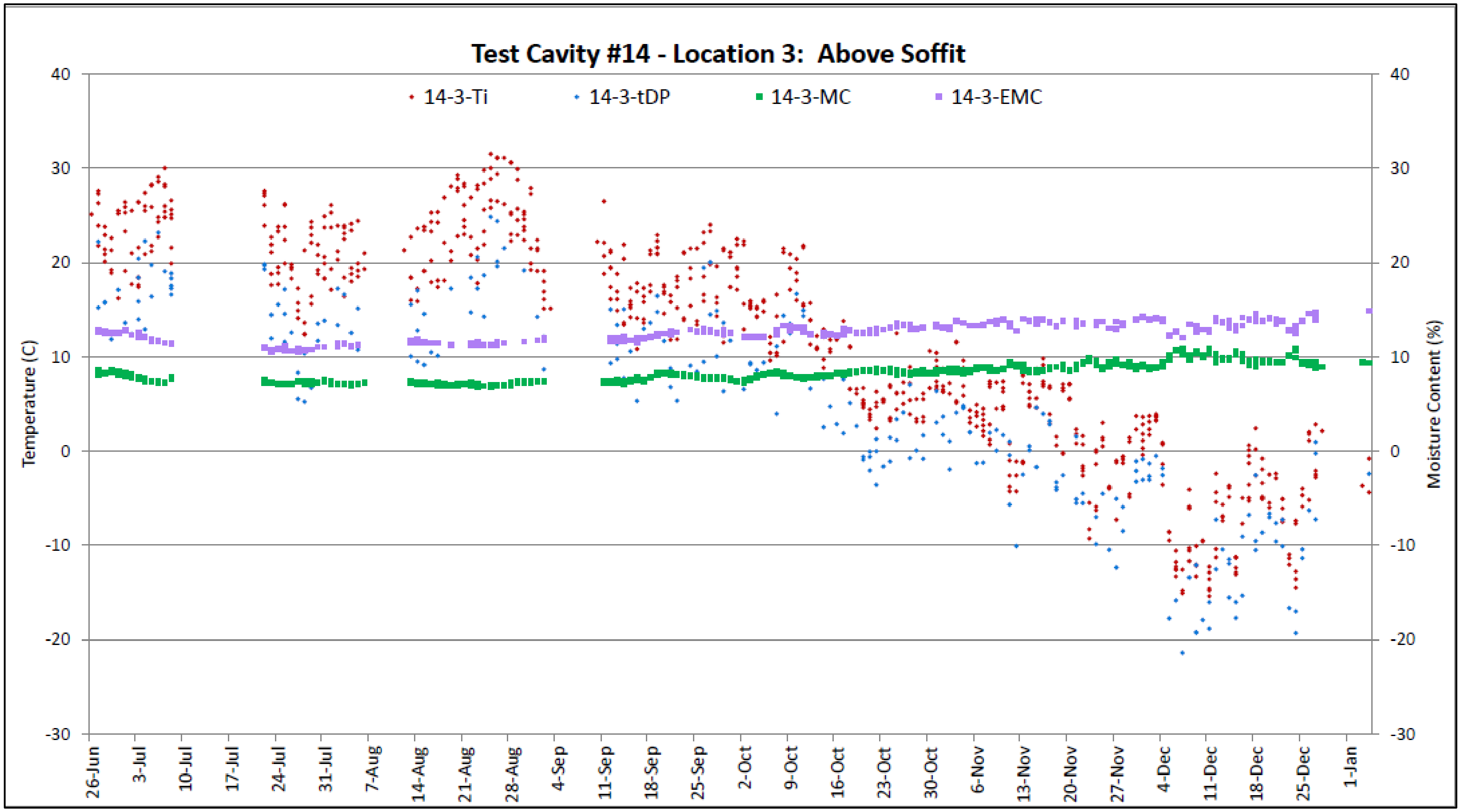


Figure 71. Moisture behavior above soffit – Spray foam insulation test cavity

Inside Soffit
Surface
Temperature

Dew
Point
Temperature

Wood
Moisture
Content

Equilibrium
Moisture
Content

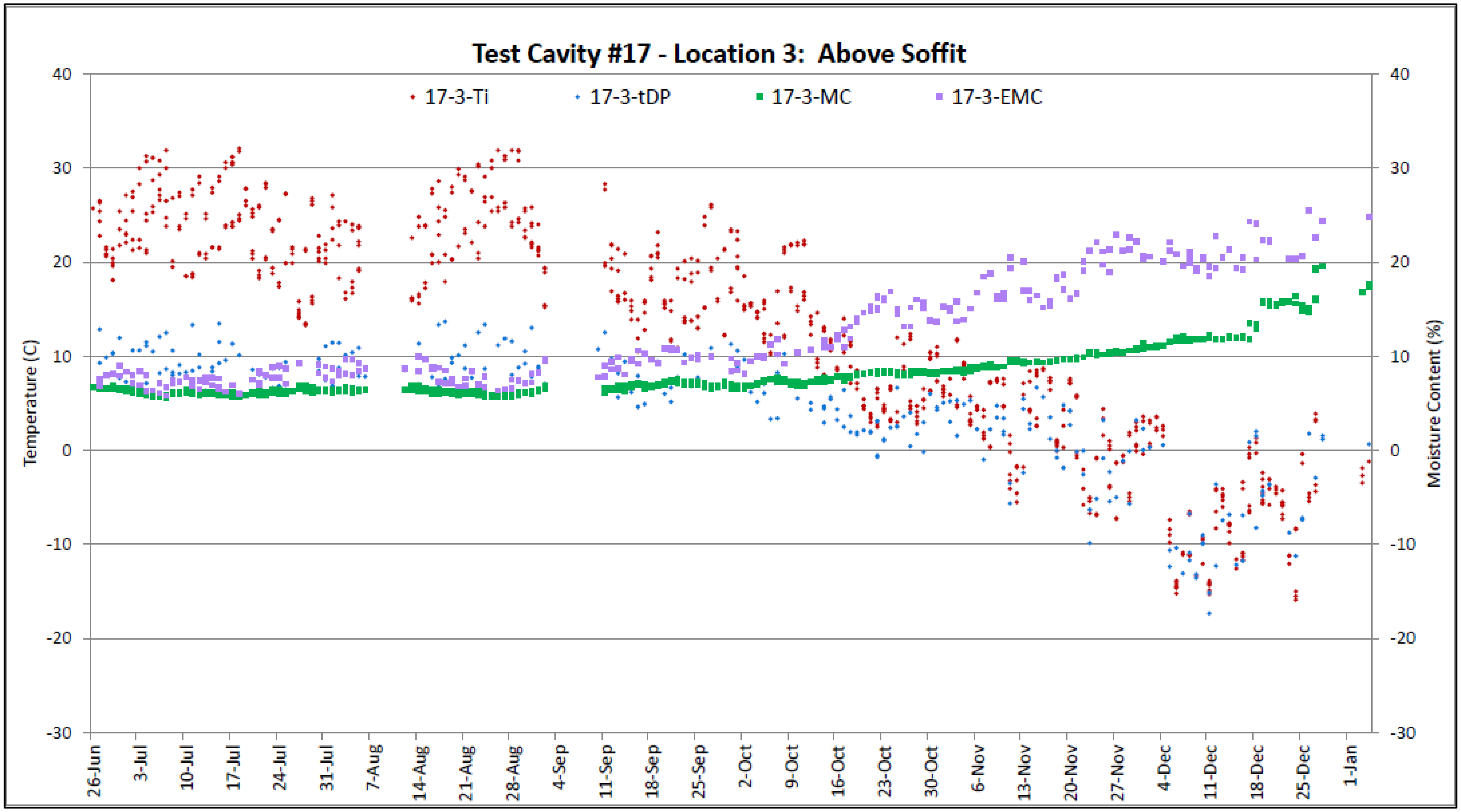


Figure 72. Moisture behavior above soffit – Open R-19 batt test cavity

Inside Soffit
Surface
Temperature

Dew
Point
Temperature

Wood
Moisture
Content

Equilibrium
Moisture
Content

The condensation and wetting potential of a surface may also be predicted by a comparison of the dew-point temperature of the air mass adjacent to a surface and the temperature of the surface. Both values are contained in the data set and are included on the same graph as the wood moisture content and the equilibrium moisture content for the twelve locations compared in Table 6. A review of the twelve graphs showed that at least once during the cold weather in December 2013, and usually more than once, the surface temperature at every one of the twelve locations on Table 6 dropped below the dew-point temperature of the air adjacent to the colder surface.

Graphs showing relative humidity at boundary locations, cavity location one (rim joist), and cavity location three (soffit) have been provided in Figures 64 through 66 to add perspective to the representations of wood moisture content, equilibrium moisture content, material (surface) temperature, and dew-point temperature provided in Table 6 and Figures 67 through 72. Graphic representations of relative humidity at all other test cavity locations and of air temperature, vapor pressure, partial vapor pressure, and humidity ratio at all test cavity locations were also reviewed.

While all the data taken together provides the most comprehensive picture of hygrothermal performance in the cantilevered floor assembly, the graphs selected for use in tables and included in this chapter most specifically addressed the questions raised by this study.

Conclusions and Recommendations

The findings of this study, based on temperature and moisture measurements recorded between June 26, 2013 and January 4, 2014 provide a good representation of a relatively uneventful summer in the cantilevered floor assembly followed by the more interesting fluctuations in temperature and especially moisture content of air and wood brought on by seasonal changes into the fall and then into winter. This study looked only at one cantilevered floor assembly, extending two feet beyond the supporting wall below. It is located on the north side of a wood framed home in Roseville, Minnesota and in DOE climate zone 6 (cold climate). The cantilever assembly was modified from its original condition to improve air-sealing details and to include three insulation types for comparison during this study. Investigation of floor surface temperatures above the cantilevered floor assembly showed insignificant difference between the different insulation strategies, but all floor surfaces were colder than optimal comfort levels.

The three insulation strategies show measurable differences with respect to moisture behavior. The cold season wetting cycle was documented in at risk locations by wood moisture content changes. Potentials for condensation and wetting, as seen through other indicators, showed the same forces at work throughout the entire cantilevered floor assembly but with different outcomes depending on the insulation and air-sealing strategy. When surface temperatures fall below the dew-point of the adjacent air mass, the air mass has to provide enough available moisture to condense on the surface and wet the wood before any change in wood moisture content will be seen. The interior of the study home is aggressively dehumidified to keep relative humidity at or below 36% RH until the seasonal change into winter creates even drier conditions. That limits the amount of moisture available to migrate into the cantilever floor cavities but higher indoor relative humidity could change the outcomes. It appears that blocking and sealing a completely filled cavity (cavities # 8 and #11) and the air-sealing properties of the spray-applied closed-cell plastic foam (cavities #5 and #14) serve to restrict mechanisms that could move moist air toward cold surfaces in high risk locations.

Based on this investigation, the open R-19 cavity appears to result in the highest durability risk. The open R-19 cavities (#2 and #17) allowed free movement of air through the fiberglass batts and the results seen in Figures 69 and 72 and Table 6 serve to raise serious concern about the moisture accumulation indicated in the open R-19 batt cavities of the cantilevered floor. The wood moisture content, particularly at the rim joist and soffit locations was at high enough percentages that it would be cause to discourage the use of the open R-19 cantilever cavity type. Still, the water stained rim joists, soffits, and joists that had been insulated with open R-19 batts and open to the basement for forty years showed no sign of decay when opened and modified to begin the current study. The original open cavities appear to have had sufficient capacity to dry before decay could begin and damage the forty year old cantilevered floor assembly.

Based on the observations of this study it appears that diligent air-sealing to control moisture behavior in the cantilever cavities is effective, even when using different insulation strategies, but it is important to consider that differences in workmanship may affect any advantage provided by the choice of a specific insulation strategy. Even after the extreme detailing to block and air-seal the R-30 cavities, results measured at the coldest surfaces indicated wood moisture accumulation at levels that could eventually become a cause for concern. If the air-sealing details were to be completed at a lower level of workmanship that allowed larger volumes of moist air to enter the closed cavities, the wood moisture content would be expected to increase to percentages that might pose a higher durability risk. The moisture activity within the closed cavities was such that further investigation, specifically of conditions in the closed cavities, is recommended.

The cavities insulated with spray-applied closed-cell polyurethane foam and left open to the basement appeared to show the best performance for both temperature and moisture. Here again, differences in workmanship and existing conditions at the time of installation could easily change the results. Environmental temperature and moisture conditions outside of recommended application parameters have been seen to result in shrinkage, gaps, voids in the finished insulation, and incomplete curing. Incorrect component ratios, application temperature, and equipment configuration can also produce a defective product. While product selection and process strategy are both important, it is workmanship that determines final product performance in the building assembly.

The data acquisition system continues to accumulate data for further study. A continuation of this investigation that looks at the moisture performance of the three different insulation strategies for the balance of the winter and through the transitions into spring and summer may provide insights and answers about the balance of the annual moisture cycle that occurs in the insulated cantilevered floor assembly in the cold Minnesota climate. Will moisture eventually find its way behind the spray-installed foam insulation or into a blocked and sealed cavity where it may become trapped and increase the potential of wood decay. Will the open R-19 cantilever insulation cavities again demonstrate the capacity to dry before durability is compromised? Further observation and investigation should provide a more complete picture of moisture behavior in cantilevered floor assemblies.

Chapter 7

Future Work

The results and recommendations of this study are based on six months of observation which included seasonal transitions from summer to fall and from fall into winter. The accumulation of data from the monitored cantilevered floor assembly continues and examination of data from a full year of observation may be completed in the future. This is expected to provide the rest of the story about wood moisture content in areas where moisture increases were recorded during the transition from fall into early winter. It will also provide a record of all monitored conditions in the cantilevered floor during winter, the transition from winter to spring and then from spring into summer. The data set for a full year may provide additional information or supplement the currently reported results and recommendations or it may be cause for a review of them.

Beyond that work, a modification of some of the cantilevered floor cavities could provide the opportunity to examine another question regarding floor temperature and comfort. A recent publication by Joe Lstiburek makes the case that leaving an air space above the insulation in a blocked and sealed floor over unconditioned space results in a warmer floor surface above. (Lstiburek, 2012) During the current investigation, one of the three insulation strategies used is the completely filled, then blocked and sealed cavity. One of the other cavity types, that with the R-19 batt at the bottom and against the rim joist, could be modified by installing an additional fiberglass batt in each cavity to bring the fiberglass batt insulation to a point two inches below the sub-floor above and then blocking and sealing the cavity in the same way and with the same materials as the existing blocked cavities. The sensors are all in place and functional, allowing for a side by side comparison of the filled and blocked cavities that are completely filled with insulation and are identical except for the air space just below the sub-floor above. There would be two pairs of cavities. One pair will have carpet on top of three quarter inch hardwood above the sub-floor and the other will have only the three quarter inch hardwood above the sub-floor.

As part of a Green Building Advisor blog exchange, it is stated that “Lstiburek’s approach – leaving an air space between the top of the insulation and the subfloor – is dangerous to follow if you are a builder with average skills, because air leaks in floor assemblies routinely allow cold exterior air to infiltrate the joist bays,” Holladay adds. “Once that happens, this detail is a disaster. The detail only works if the builder has impeccable air sealing skills. That’s rare, but possible.” (Holladay, 2013) This discussion is not completely new and different. In an October 2006 exchange of e-mails with Joe Lstiburek (Building Science Corp.) and Brad Oberg (IBACOS) on the related subject of rooms over garages and the placement of cavity insulation was discussed. Joe Lstiburek advised that there was a comparison to wall insulation which could be held to either the inside or outside of the wall assembly, but holding it to the outside “made the interior plaster surface warmer.” He stressed the importance of carefully executed air-sealing details and advised using the heat loss calculations from ASHRAE Fundamentals to model the assembly. (Lstiburek, 2006) Brad Oberg also responded to my question about insulation placement by explaining that in a floor over a garage “the insulation must be in complete contact with either the floor air barrier layer or the gypsum ceiling.

It must be continuous and if it is on the lower level, the perimeter must be carefully insulated and air sealed, and all the penetrations from the framing space to areas above and interior volumes should be sealed as well." (Oberg, 2006) While this discussion addressed floors over garages, it may support the concept of holding the insulation down against the bottom of the cantilever assembly. In both cases, the strongly stated advice was to completely seal all seams and penetrations of each floor enclosure. This is in contrast with the Wagner text cited in an earlier section and the opinions of some builders and insulators where blocking and air-sealing is not included in the cantilever insulation method. If this additional deployment of the existing research cantilever is made, the outcomes should be interesting.

One additional extension of the research using this cantilever has been suggested. Following a currently popular method of adding thermal insulation to existing homes, rigid foam insulation board could be added to all surfaces of the exterior of the home during a complete energy retrofit. The existing sensors, if still functioning, could record a year of temperature and moisture data to compare to the baseline data currently being collected.

Future studies would help to extend the return on investment of the installed data acquisition system and add new layers of information to what is known about the hygrothermal performance of residential cantilevered floors.

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