Insulation Retrofits to Address Wall/Ceiling Moisture Damage

William B. Rose1, Jeffrey R. Gordon1

Abstract
A common site of moisture damage, discoloration and mold growth, usually found in houses with truss construction and low-slope roofs in heating climates, is located at the juncture where the ceiling meets the exterior wall. The aim of this research was to determine if insulation retrofits could improve the thermal conditions at the wall-ceiling juncture and thereby reduce the likelihood of mold growth or other discoloration.

Three treatments were identified. Two treatments required opening of the soffit and adding insulation from the exterior: the “pack” treatment where fiberglass and rigid foam insulation were packed into poorly-insulated cavities, and the top plate “pillow” treatment, where a pre-formed foam unit was pre-cut to fit. A third treatment was from the indoors and consisted of an interior insulating “crown” molding fitted into the corner. Eighteen study houses were monitored over one winter in Belcourt, N.D. Each of the three treatments was applied to five homes. In addition, three homes received all three treatments plus one room with no treatment (control), and were cabled for thermocouple measurements.

Temperatures at the wall/ceiling juncture were found to be consistently colder at the truss location as compared to the cavity between the trusses. All three treatments provided upgraded thermal conditions at the cavity, with the interior insulating crown providing the greatest benefit. All three treatments provided little to no improvement at the truss locations. Ultimately, the thermal bridging that results in the temperature depression at the truss was not remediated by any of the insulation techniques. This research found that potential thermal improvements through insulation fail to significantly improve the thermal conditions at the truss. Efforts to reduce distress at the wall-ceiling juncture need to be targeted toward interior winter moisture control. New approaches involving cutting the overhang, allowing the wall insulation to continue without interruption to the roof or ceiling insulation, and rehanging of the overhang, could be promising.

Background
In heating climates, a common location of wintertime moisture and mold problems is at the wall/ceiling juncture of exterior walls (Figure 1). The problem is most commonly seen in houses built within the last 50 years following the advent of light-frame wood trusses. The proliferation of condensation-based problems at this location indicates a persistently cold location, resulting from:

1. Insufficient insulation. Limited space and installation access result in low levels of insulation over the top plate. In many cases, cardboard or wood blocking was installed to prevent blown-in insulation from escaping the ceiling cavities into the soffit, thus leaving the top plate bare of insulation.

Figure 1: Wall/Ceiling juncture moisture problem

1 Building Research Council/School of Architecture, University of Illinois at Urbana-Champaign
2. **Cold convective wind currents through the soffit.** Soffits were often intentionally ventilated as part of a roof ventilation system, allowing cold air to pass directly over the top plate of the wall, degrading the thermal performance of insulation.

3. **Thermal Bridging.** Regardless of insulation, the bottom chord of the truss acts as a thermal bridge to the exterior.

4. **Corner geometry.** At any corner, the ratio of exterior surface area to interior surface area is greater, resulting in more heat loss compared to other locations of the exterior walls and ceilings. Just as critical, the slow-moving currents of warm interior air tend to shortcut the corner, resulting in a greater insulating interior air film at the corner.

This paper reports on a field study that tested three insulation retrofit approaches designed to reduce or eliminate condensation-based moisture conditions at the exterior wall/ceiling junction.

**Field Location**

The field study was performed at the Turtle Mountain Reservation in northern North Dakota during the winters of 2003 and 2004. A previous site visit had revealed numerous cases of houses exhibiting moisture problems at the wall/ceiling juncture. The Turtle Mountain Housing Authority (TMHA) assisted in the site selection, installation, and monitoring of the project. 18 single-family houses of identical age and style were selected in the Shell Valley development for participation in the study (Figure 2). Upon examination, all of the houses had identical top plate construction. Upright 2”x4”s had been installed on the inside of the top plates to contain the original blown cellulose insulation in the attic, a detail that can be seen in Figures 3 and 4.

**Insulation Methods**

Three methods of retrofitting insulation at the wall/ceiling juncture were developed for testing:

1. **Exterior Top Plate Pillow**
   This insulation technique focused on the development of a manufactured insulating foam insert designed to fit between the chords of a light-frame truss and insulate the exterior face and upper surface of a double top plate. The most suitable material identified was a white polypropylene foam insulation. The final design of the pillows was an “L-shaped” profile with each leg 2” in thickness, and 22 ½” long to fit between truss spaces (Figure 3).
1. Exterior Insulation Pack
The exterior insulation pack strategy used common insulating materials. Fiberglass insulation, measured and removed from batt insulation, was placed above the top plate, and sealed in place with a 1” thick rigid foam attached to the outside of the double top plate (Figure 4). As with the pillow approach, installation required access through the exterior soffit.

2. Interior Insulating Crown Molding
The interior insulating crown molding consisted of pre-fabricated foam crown molding installed on the interior of the wall/ceiling junction (Figure 5). The intent of the design was to transfer the coldest exposed portions of the wall and ceiling inward, taking advantage of conductive heat transfer from the better insulated portions of the wall and attic cavities. The final design was a 6” by 6” profile composed of expanded polystyrene, and covered with a smooth, paintable, fire-rated coating. The molding was glued into place with polyurethane foam, and sealed to the wall and ceiling with latex acrylic caulking.

Research Design
The research design called for eighteen houses to receive retrofit insulation treatments. The houses were divided into two groups:

Group I. Each of the three insulation methods was installed on five houses. Thus, Group I consisted of fifteen houses total, each house retrofit with one specific
insulation method on the north elevation.

Group II. Three houses received all three methods of insulating treatment, each treatment on a section of the north elevation. In these cases, the roof joist cavities were divided into four groups. Each of these houses had an uninsulated section of cavities to serve as a control, along with one section for each of the three insulation treatments. Figure 6 illustrates the typical layout of treatment methods in the Group II houses at Shell Valley.

Data from both groups of houses was collected to examine the thermal performance of the retrofit insulation treatments. In Group I houses, thermographic images of the wall/ceiling juncture were taken in each of the fifteen residences over the course of the winter. The research design called for one set of images to be taken each week in the study houses during the coldest winter months, from December through February. During a visit to each house, one thermographic image of the wall/ceiling juncture was taken in each of the three rooms on the north elevation. For each image, the house number, room, date, time and image number were recorded to document the images.

Group II houses were hard-wired to record wall/ceiling juncture temperatures. Each house was equipped with a datalogger that monitored and stored data from twelve single-ended Type T thermocouples. Each of the three insulation methods incorporated in these houses, along with the uninsulated control space, received the thermocouples.

**Instrumentation**

*Infrared Instrumentation – Group I Houses*

Thermographic images were collected with an instrument that uses a 120 element linear array of uncooled thermoelectric detectors to measure temperature. With this thermal imager, the array is aligned vertically, and scans horizontally over 1.5 seconds (exposure time) to collect a 120 x 120 matrix of temperatures. Thus, each thermal image is a collection of 14,400 temperature values. The Camera has a listed accuracy of 3° C or 3% of full scale. Emissivity and background temperature settings are programmable. For this project, emissivity was set at .90 and background temperature at 70° F for all thermal images. Thermographs are stored on a PC memory card that can be offloaded to a PC for storage and analysis. The instrument has a 17.2 degree field of view. With a standard distance of five feet from the wall/ceiling juncture, the resulting images captured an area approximately 18” x 18”. As a result, each of the temperatures captured in a thermal image represents an area of 0.0225 in², or slightly greater than 1/8” x 1/8”.

Thermal imager has a dedicated software program, containing image analysis tools. The data collected by the imager can be viewed as a spreadsheet matrix of 14,400 values, or as a color enhanced thermal image. With the software, maximum, minimum, and mean temperatures can be identified in any area of the image.

*Datalogger Instrumentation – Group II Houses*

Each Group II house was equipped with a datalogger and twelve thermocouples. Thermocouple measurements were made using 24 ga. Type T thermocouple wire with twisted ends. The two exterior treatments, along with the uninsulated control bays, were monitored with two thermocouples: one placed at the wall/ceiling juncture beneath a truss (as determined by a stud finder), and the second placed at a cavity location between trusses. For the interior insulating crown molding, four thermocouples were put in place similar to the others, but at both the top and bottom of
the molding. Finally, two thermocouples were placed in the wall ceiling juncture at each of the outside corners of the house. All thermocouples were placed directly in contact with the wall/ceiling juncture corner. The internal temperature at the datalogger was used as the reference temperature for the thermocouples. Dataloggers were programmed to download temperature data at one hour intervals throughout the winter.

A weather station was installed at the Shell Valley community building adjacent to the test houses. Measurements taken at the weather station were: 1) temperature with radiant protection, 2) relative humidity, 3) insolation (solar radiation), 4) wind speed and 5) wind direction. Outdoor temperature measurements from the weather station were used in this analysis. As with the Group II houses, the weather station was programmed to download data at one hour intervals throughout the winter.

Each house received an additional wireless datalogger measuring temperature and relative humidity. They were placed in a central room with the datalogger, and programmed to capture and store temperature and relative humidity data every hour. Expected temperature total error or the sensors is +/- 1°C (+/- 2°F).

**Data Collection and Management**

By necessity, data collection was performed by two TMHA staff members. In November 2004, BRC researchers traveled to the TMHA to perform a training session on data collection and data transmittal. Written protocols were prepared for both phases of data collection: collecting images with the infrared camera and data retrieval from the Campbell dataloggers. The BRC provided the TMHA with a laptop computer for data collection at the four dataloggers. Use of the infrared camera was demonstrated, and the camera, tripod, and memory cards left with the TMHA.

Pre-labeled mailing envelopes were prepared for the TMHA for the transfer of memory cards (IR images) and floppy disks (datalogger). Data log sheets and coversheets were also prepared to document each data transfer. Additionally, protocol was established for sending electronic versions of Campbell data.

Upon receipt of a data package, data was downloaded to dedicated files and maintained on the BRC server. Data verification was performed on the submitted thermal images. Images were discarded from the dataset for several reasons:

1. Unclear or out-of-focus images
2. Images that did not clearly delineate the wall/ceiling juncture
3. Images that were not clearly documented for insulation treatment
4. Images with questionable numbering or agreement with the submitted log sheet.

**Analysis**

*Analytical Approach*

The magnitude of the temperature depression at the wall/ceiling juncture is dependent on the exterior temperature. Because the exterior temperature varies over the course of the winter, the absolute temperature depression at the wall/ceiling juncture (in degrees) does not provide comparable values between measurements. In order to have comparable values for analysis, the temperature depression required conversion. The basis of the temperature analysis used in this report is “Percent temperature drop” ($D$).

\[
D = \frac{\Delta T_{i-s}}{\Delta T_{i-o}}
\]
where
\( \Delta T_{i-s} \) is the difference in temperature between indoor air and the wall/ceiling surface, and
\( \Delta T_{i-o} \) is the difference in temperature between indoor air and outdoor air.

Essentially, D is a percentage value that indicates the extent to which the wall/ceiling jun-
cature is thermally "outside". A high value of D indicates poor thermal performance and greater risk of moisture problem at the juncture. A low value of D indicates that the surface is well-insulated from the interior and is at lower risk of moisture and mold problems. By stating the temperature depression as a percentage, the exterior temperature is independent of variations in exterior temperature, and analysis of thermal performance can be conducted with all verified temperature values.

**Thermal Performance by Infrared Photography – Group I Houses**

Infrared images were gathered in the Group I study houses beginning in February. A total of 345 images were submitted for analysis. Following a verification process, a total of 203 images were available for data analysis. With respect to the three insulation treatments, 63 crown, 80 pillow, and 60 pack images could be analyzed. There were a few thermal images of control bays in the Group II houses, but not a sufficient number for comparative analysis.

Temperature was measured in only one room of the house. However the images were made in different rooms. A substantial difference in room temperature would effect the calculation of delta T, and subsequently of D. For this reason, a method to estimate the delta T was required for the infrared images.

In each thermal image, a maximum temperature could be identified. It is reasonable to as-
sume that the maximum temperature in each image is closely related to the room temperature. Be-
cause the thermal image is of two surfaces at the thermal boundary (wall and ceiling), one would also expect that the maximum image temperature to slightly underestimate the room temperature.

**Table 1: Calculated \( D \) for thermographic images**

<table>
<thead>
<tr>
<th>Pillow</th>
<th></th>
<th>Pack</th>
<th></th>
<th>Crown</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>House #</td>
<td>Truss</td>
<td>Cavity</td>
<td>House #</td>
</tr>
<tr>
<td>3 Wired</td>
<td>43%</td>
<td>33%</td>
<td>3 Wired</td>
<td>40%</td>
</tr>
<tr>
<td>540</td>
<td>40%</td>
<td>33%</td>
<td>535</td>
<td>41%</td>
</tr>
<tr>
<td>545</td>
<td>41%</td>
<td>31%</td>
<td>536</td>
<td>41%</td>
</tr>
<tr>
<td>547</td>
<td>45%</td>
<td>37%</td>
<td>537</td>
<td>45%</td>
</tr>
<tr>
<td>548</td>
<td>47%</td>
<td>35%</td>
<td>550</td>
<td>44%</td>
</tr>
<tr>
<td>549</td>
<td>35%</td>
<td>28%</td>
<td>544</td>
<td>na</td>
</tr>
<tr>
<td>All</td>
<td>41%</td>
<td>32%</td>
<td>All</td>
<td>43%</td>
</tr>
<tr>
<td>St Dev</td>
<td>9%</td>
<td>7%</td>
<td>St Dev</td>
<td>8%</td>
</tr>
<tr>
<td>N =</td>
<td>79</td>
<td>77</td>
<td>N =</td>
<td>64</td>
</tr>
</tbody>
</table>

Of the 203 images available for analysis, a total of 65 IR images were in rooms with a sen-
sor, and the actual room temperature was recorded. For these images, delta T was calculated twice, once using the known room temperature from the sensor, and once using the maximum im-
age temperature. As anticipated, there was a strong relationship between the two calculations (ysensor= 0.94ximate +7.39, R2 = .82). Also as expected, the delta T as calculated from the sensor was typically higher than the delta T as calculated by the maximum temperature in the thermal image (difference in mean = 4.43o F, median = 4.41o F, standard deviation = 0.50 F). Given this evidence, for the analysis, the delta T in images without a corresponding sensor temperature were
converted by the linear equation defining the correlation. This generally led to an increase in delta T of around 4.4°F. For images with a sensor room temperature value, the room temperature value was used in calculating the delta T. From these delta T values, the percentage D could be calculated.

Table 1 presents the calculated D for the thermographic images. The two exterior methods had nearly identical thermal performance both at the truss and at the cavity. Mean temperature at the truss was 41% and 43% toward the exterior temperature, respectively. At the cavity, both exterior methods had a mean calculated D of 32%. The interior insulation crown shows a slight improvement at the truss (38%), and a clear improvement at the cavity (22%).

Thermal Performance by Thermocouple Measurement – Group II Houses

At three houses twelve thermocouples were used to measure surface temperature at different locations at the wall-ceiling juncture. In these three houses, all three of the treatment types were used (crown, pillow and pack), and one section of the eave was left untouched as a control. All of the treatments were on the north side of the house only. For the three houses with cabled sensors, the results, expressed as percent temperature drop D are given in Table 2.

<table>
<thead>
<tr>
<th>TABLE 2. Results of cabled temperature measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>-------</td>
</tr>
<tr>
<td>541</td>
</tr>
<tr>
<td>554</td>
</tr>
<tr>
<td>539</td>
</tr>
<tr>
<td>average used</td>
</tr>
</tbody>
</table>

1Average of houses 554 and 539. House 541 was not used.
2“Average used” was from House 539 only. House 541 was not used. Thermocouples at the crown in house 554 malfunctioned.
3Wall conditions used were averages of houses 554 and 539, and only one value is reported for the two measurement sites.
4Average of houses 554 and 539.

Table 2 shows several findings that require explanation.

- House 541 shows negative values for D. This could only happen if the measured thermocouple values were greater than the measured interior temperature (located in the room with the control bays), which was obviously the case at this house. It seems apparent that the center room in this house was considerably colder than the other rooms of the house. Additionally, upon removal of the thermocouples it was found that several sensors had pulled away and were no longer fastened to the corner. Data from this house is not used in the reported averages in the table or the following analyses.

- Temperature sensors for crown-cavity-ceiling and crown-truss-ceiling in house 554 went out of operation early in the study and are not reported here.

- For the reasons explained above, the “average used” in the table for the two exterior insulation treatments (pillow and pack) is the average of houses 554 and 539. The “average used” for the interior crown includes House 539 only. These averages are also used in the following analyses.

- With respect to the interior crown, the measured wall surface temperatures (at the bottom of the crown) remained just as warm (or warmer) than the ceiling surface temperatures. For this reason, they are not given as part of the remaining analysis.
Based on temperature measurements by thermocouple, the value of the proportion D was considerably less than the value based on the temperatures from the thermal images. The basic relationships—between insulation methods and between truss and cavity positions—were largely the same. These relationships are explored in the following analyses.

Results

As the temperature results make clear, there was a considerable difference between the thermocouple temperature measurements at the wall/ceiling juncture and the values detected using infrared thermography. The thermal images indicated much colder surface temperatures, while the thermocouple temperatures were much higher, i.e. much closer to the room air temperature. Generally, calculated D by thermography was approximately half of the calculated D by thermocouple measurement at both the truss and the cavity. At the cavity, for instance, D varied between 10% and 14% by thermocouple, and between 22% and 32% by infrared imaging.

In the conditions of the study, it is likely that the thermocouple measurements err in being too high. The thermocouples were prepared on site, so the leads were attached mechanically by twisting rather than by soldered connection. The ends of the connected pair were trimmed so that the resulting length of the twisted connection was approximately ¼”. The thermocouple was fastened to the ceiling with a staple approximately 1” to 2” away from the temperature-sensing end. The intent was to have the entire sensing length situated tightly in the corner formed at the wall-ceiling junction. Some measure of imperfection can be expected with this design.

There are several obvious reasons for the difference in the two temperature measurements:  
1. The means of attachment for the thermocouples was sufficiently loose that the sensing head was capable of drifting away from the surface, and this drift was noted upon disassembly. The amount of drift varied from house to house and from location to location. The drift was greatest in the first house to receive the installation and was least in the last house—a learning-curve effect.  
2. Even if the thermocouple attachment had maintained good surface contact, there is radiant exchange between the exposed sensing head and the entire room.  
3. The wire used was 24 gauge, allowing some thermal conductivity of room air temperatures along the wire length. Given the lengths of thermocouple wire used and the required ruggedness of the installation, this heavy a gauge was necessary.  
4. In examining thermal images, the minimum temperature was easily and dependently found. In placing the thermocouples, a stud sensor was used to determine the location of the truss. This resulted in imprecision in assuring that point of lowest surface temperature. While the minimum temperature was always identified by thermal imaging, thermocouple placement was a “best guess” placement.  
5. The thermocouple sensor tip was relatively long, and so, to the extent that it did measure surface temperature at the juncture, it averaged it over that length. The IR methods focused on a small point, approximately 1/8” x 1/8”, and assured greater resolution.

Given all of these factors, it is reasonable to conclude that the thermal images provided the most accurate measure of minimum temperature at the wall/ceiling juncture. Thermocouple measurements, while erring on the warm side, did provide acceptable relative relationships between methods and placements.

Modeling Analysis

In addition to the instrumentation used in order to characterize the temperature drop at the wall ceiling juncture, the conditions were modeled. The control eave detail and the three treat-
ments were modeled for 2-D heat flux using Lawrence Berkeley Laboratory software THERM 5.1. Thermal conductivity values of building components were taken from ASHRAE Handbook 2005 Fundamentals Chapter 25. Exterior temperature of 0 degrees Fahrenheit is the default value; the exterior surface film conductivity default value is 4.6 Btu/(hr-ft²-°F). An interior temperature of 73°F was selected based on the measured data.

The thermal insulating value of the materials is rather well known, although the thermal insulating value of wood may change with changes in moisture content—an effect not applied in this modeling. However, the heat transfer characteristics of the interior and exterior air films are not known, and they must be expected to vary along the length of the affected corner, and they may change over time. They are a wildcard in modeling—there is no best direction to selecting a value, and the outcome (surface temperature depression) is strongly a factor of the choice of air film resistance value of a corner. ASHRAE Handbook of Fundamentals Chapter 25, Table 1 gives the surface conductance and resistance for air. With a surface emittance of 0.82 (appropriate for painted surfaces) the thermal resistance value of a plane surface for still air varies from 0.61 to 0.92 (hr-ft² degF)/Btu. In a corner, the air is expected to be less likely to move from convection, and the surfaces provide some radiant exchange between them. For those reasons, the thermal resistance of an air film in a corner is expected to be higher than the value along a flat plane. The air film resistance value selected here is 1.0 (hr-ft² degF)/Btu.

The results of the modeling study are given below in Table 3. The percent modeled temperature drop (D) is calculated from the minimum temperature as described above. The U-factor is the estimate of the thermal conductivity of the assembly, which correlates with minimum temperature estimates.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>model</td>
<td>31%</td>
<td>36%</td>
<td>15%</td>
<td>31%</td>
<td>20%</td>
<td>22%</td>
<td>36%†</td>
<td>22%</td>
<td>36%</td>
</tr>
<tr>
<td>U-factor:</td>
<td>0.220</td>
<td>0.316</td>
<td>0.129</td>
<td>0.279</td>
<td>0.129</td>
<td>0.180</td>
<td>0.316</td>
<td>0.181</td>
<td>0.316</td>
</tr>
<tr>
<td>modeled (Btu/ (hr-ft²-F))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pillow-truss and pack-truss assemblies are identical to control-truss

Figures 7 and 8 show the results of the modeling in schematic form. Isotherms are drawn on the detail sections. Widely spaced isotherms represent high thermal resistance, and squeezed lines represent high thermal conductivity. A software command “View temperature” was used to identify the lowest surface temperature at the juncture location. For the truss conditions using two-dimensional modeling, there is no difference between the control, pillow and pack conditions. In the discussion below, they are assigned the same value for modeling purposes.

**Figure 7.** Modeling outcomes of pillow (left) and pack (right). Conditions at the truss are identical to the conditions in the control for pillow and pack.
Figure 8. Modeling outcome of control (left) and crown (right). Conditions at the cavity and truss were modeled. Curved lines are isotherms or lines of constant temperature.

Figure 9. Percent temperature reduction ($D$) at cavity in control and three insulation treatments. $D$ is characterized using three methods.

Figure 10. Percent temperature reduction ($D$) at the truss condition for control and three treatments. $D$ is characterized using three methods.
Comparison of insulation treatments for effectiveness

Having modeled the thermal conditions at top plate, it is possible to compare the insulation treatments based on three values: measured by thermocouple, measured by IR image, and by the results of the model. Figure 38 presents the results at the cavity conditions. The findings tend to show good performance of the treatments at the cavity.

The three methods of characterization give different results. This is to be expected. Measured thermocouple values give low values for D indicating the surface temperature measurements were warm. IR readings showed cold surface temperatures, so the values for D were high. Modeled values came between these two extremes. The relationships within each method, however, indicate consistent results. Based on the measured thermocouple values:

- The top plate pillow warmed the cavity by 6% of total delta T over the control
- The pack insulation warmed the cavity by 6% of total delta T over the control
- The interior crown warmed the cavity by 8% of total delta T over the control

Based on the modeled values:

- The top plate pillow warmed the cavity by 9% of total delta T over the control
- The pack insulation warmed the cavity by 9% of total delta T over the control
- The interior crown warmed the cavity by 16% of total delta T over the control

Due to the low number of thermal images of control bays submitted, there were no dependable control values for the thermal images values.

All methods served to warm the cavities between the trusses. Of the three treatments, the crown treatment provides the greatest reduction and the greatest benefit. Pack and pillow treatments provide benefits but they are not quite as substantial as the crown. The upright 2 x 4 block on the top plate at the Shell Valley houses, which prevented the continuity of insulation from exterior to interior on the two exterior insulation treatments, likely inhibited the performance of these treatments. With a more typical detail, the exterior insulation treatments might meet the performance on the interior insulating crown.

As all of the data and analysis has shown, the condition at the truss is more critical than the condition at the cavity. Because of its thermal bridging effect, it is the truss condition that shows the lowest surface temperature, and a corresponding temperature drop (D). Figure 39 provides a comparative analysis at the truss. For the truss location the results are more ambiguous. Regarding the two exterior insulating treatments:

- Thermal images show quite cold temperatures, with D exceeding 40% in both cases.
- Modeled values show no improvement, because the model value at a truss is identical to the control. Exterior insulation can only be applied between the trusses, in the cavity spaces, and thus the model does not change in this case.
- Using measured thermocouple values, the pillow and pack treatments show some slight benefit. The top plate pillow improved the temperature by 3% of total delta T, and the pack insulation by 2%. Due to difficulties explained earlier, these numbers are based on only one control house (539 Shell Valley). This minor improvement may be due to three-dimensional heat conduction from the warmer cavities to each side of the truss.

Exterior treatments cannot address the thermal bridging at the truss. If there is any improvement in thermal conditions from these treatments, it is slight. The findings relating to the interior crown treatment are possibly more ambiguous:

- Measured thermocouple values indicate that the conditions at the crown are unimproved, and indeed worse than the conditions resulting from the exterior insulation methods.
• Thermal images show a small (5% of delta T) improvement compared to the exterior treatments, though comparison to a control is unknown. (If one presumes the relative values for the images are similar to the measured thermocouple values, a control value of 47% is obtained)

• Modeling indicates that the crown makes a small improvement (5% of delta T) over both the control and the exterior treatments.

While the results are conflicting, it is clear that the interior crown does not provide a significant temperature reduction at the truss. In order to see why this might be the case, Figure 34 begins to provide an answer. The crown provides insulation at the interior of the assembly. Thus it tends to chill the bottom chord which is outboard of the insulation toward the eave. Toward the room, the bottom chord is heated by the room. The midpoint of these two conditions is at the edge of the crown insulator, so we would expect a temperature at that location that is a midway value between the warm and cold conditions. In other words, the crown does not warm up the bottom chord so much as it transfers the cold point of the truss inward.

In addressing the moisture problem at the wall/ceiling juncture, the coldest and most critical temperature is at the truss. Retrofit insulation treatments cannot significantly change the temperature at the truss.

**Humidity analysis**

If a building surface temperature is sufficiently cold, moisture accumulation can occur and it can sponsor the growth or mold or mildew. Two different values are used for making the estimate of mold growth potential. For mold to inoculate a clean surface, research has shown that the surface must be essentially wetted, i.e. the temperature of the surface must reach the dewpoint of the indoor air, and it must remain wetted for a substantial period of time. For the surface to permit established mold to grow, the relative humidity of the air right at the surface must be at 80% RH or more, on average, for one month. Therefore, we can determine the likelihood of new or established mold growth at the wall-ceiling juncture if we know the following:

- Winter outdoor temperature
- Indoor humidity, and
- Percent temperature drop (D).

All three of these characteristics have been characterized as part of this study, and average values are presented here. Table 4 examines the potential for mold in the nine study houses that had full moisture data gathered by the wireless sensors.

In Table 4, we see that there was a range of indoor humidities in the various houses. The driest house (lowest dewpoint temperature) was house 549, and the wettest was house 554. The average outdoor temperature during the period of study was 13.1 degrees F. That value is used for each house listed in Table 4. In order to reach dewpoint, the wettest house must exhibit a D value of 31%, and for established mold to grow, that house must exhibit a D value of 20%. Values in this range were found in the course of the study. However, the driest house, 549, showed very high D values that must be attained in order to cause mold-growth—84% for dewpoint and 76% for established growth—and D values this high were not found as part of this study.

---

Dewpoint is calculated from average temperature and average Relative Humidity (RH). 

\[ D = \frac{\Delta T_s}{\Delta T_{io}} \]

where \( \Delta T_s \) is the temperature drop from inside to the wall surface and \( \Delta T_{io} \) is the temperature drop from inside air to outside air.

Temp at 80%rh is the temperature of the air that results from cooling the sample air down to 80% relative humidity. It is similar to dewpoint temperature, which is the temperature of the air that results from cooling the sample air down to 100% relative humidity. While mold may require RH at the surface of 95% to 100% for mold germination, mold may recur at relative humidity at the surface of approximately 80%.

**D** at T80% is the temperature depression ratio necessary to achieve 80% relative humidity at the wall surface, assuming uniform vapor pressure in the room.

Ultimately, the determining factor in the humidity analysis is the relative humidity of the houses. While the small potential gains in thermal performance can help a house that is marginal, retrofit insulation does not have sufficient benefit to bring a problem house under control. The moisture load in the house is the driving force that determines moisture accumulation and mold contamination at the wall/ceiling juncture.

### Conclusions

A study was conducted that aimed to measure the thermal improvements to the wall/ceiling junction of existing housing using three retrofit insulation treatments, two exterior treatments and an interior insulating crown molding. Conditions at the cavity and at the truss were measured and modeled.

Field studies are always subject to practical problems, and this study was no exception. Nevertheless, the resulting data was sufficient to use in drawing conclusions.

1. Cold interior surface temperatures will vary in proportion to changes in the outdoor temperature. A means of expressing this proportionality was developed and applied in this study.
2. At the wall/ceiling juncture during winter, surface temperatures at the truss location are lower than at the cavity, so the truss is the critical condition in solving the wall/ceiling problem.
3. The two exterior insulation treatments had almost identical thermal performance.
4. The thermal performance at the cavity showed improvement with all the insulation treatments.
5. Thermal conditions at the truss showed only marginal improvement, at best, with all insulation treatments. There was some indication that the exterior treatments made a slight improvement. The findings for the interior crown were more ambiguous.

<table>
<thead>
<tr>
<th>house</th>
<th>room</th>
<th>treatment</th>
<th>Average Indoor Temp.</th>
<th>Average Indoor RH</th>
<th>Dewpoint</th>
<th>D to avoid dewpoint</th>
<th>Temp. at 80%rh</th>
<th>D to avoid T80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>bedroom</td>
<td>pack</td>
<td>70.1</td>
<td>38.8</td>
<td>43.1</td>
<td>47%</td>
<td>49.0</td>
<td>37%</td>
</tr>
<tr>
<td>549</td>
<td>living</td>
<td>pillow</td>
<td>73.4</td>
<td>27.2</td>
<td>23.1</td>
<td>84%</td>
<td>28.0</td>
<td>76%</td>
</tr>
<tr>
<td>547</td>
<td>living</td>
<td>pillow</td>
<td>71.8</td>
<td>39.3</td>
<td>46.6</td>
<td>43%</td>
<td>52.6</td>
<td>33%</td>
</tr>
<tr>
<td>545</td>
<td>kitchen</td>
<td>pillow</td>
<td>75.0</td>
<td>37.2</td>
<td>45.0</td>
<td>49%</td>
<td>51.0</td>
<td>39%</td>
</tr>
<tr>
<td>540</td>
<td>kitchen</td>
<td>pillow</td>
<td>71.6</td>
<td>35.1</td>
<td>39.9</td>
<td>54%</td>
<td>45.6</td>
<td>45%</td>
</tr>
<tr>
<td>538</td>
<td>kitchen</td>
<td>pack</td>
<td>73.3</td>
<td>32.9</td>
<td>41.5</td>
<td>52%</td>
<td>47.3</td>
<td>43%</td>
</tr>
<tr>
<td>537</td>
<td>kitchen</td>
<td>pack</td>
<td>71.5</td>
<td>29.3</td>
<td>32.0</td>
<td>68%</td>
<td>37.4</td>
<td>59%</td>
</tr>
<tr>
<td>541</td>
<td>bedroom</td>
<td>all 3</td>
<td>71.4</td>
<td>29.6</td>
<td>35.3</td>
<td>62%</td>
<td>40.8</td>
<td>53%</td>
</tr>
<tr>
<td>554</td>
<td>bedroom</td>
<td>all 3</td>
<td>72.6</td>
<td>49.4</td>
<td>54.4</td>
<td>31%</td>
<td>60.8</td>
<td>20%</td>
</tr>
</tbody>
</table>
6. An analysis of the moisture conditions (relative humidity and dewpoint) in 9 of the 18 study house determined that the treatments may offer help in 3 of 9 cases. These cases were marginal, based on houses with borderline moisture problems. Overall, the determining factor for wall/ceiling moisture problems was relative humidity.

Discoloration and mold contamination at the wall-ceiling juncture is found in homes built with rafters or trusses, before the introduction of raised-heel trusses. This research sought to determine if the problem could be solved using means of retrofitting insulation in these houses. Retrofitting insulation is not likely to produce the desired benefits. A better strategy is to promote humidity control in affected houses.

An approach not studied here would involve 1) cutting the overhang so that the roof framing stops at the exterior of the wall framing, 2) running exterior insulating sheathing up so that it is continuous with the roof/ceiling insulation, and 3) providing a new or rebuilt overhang as an accessory outboard of the insulating sheathing. This approach would address thermal bridging at the truss which is at the heart of the problem in this study. Providing attachment of an overhang through insulating sheathing to resist wind loads would require further study.

Acknowledgements

This research was part of a Healthy Homes Technical Study funded by the US Department of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control through their Healthy Homes Initiative and Lead Technical Studies Grants program.

The research was undertaken with the generous cooperation of the Turtle Mountain Tribe in Belcourt, North Dakota. Their tribal leaders, housing staffs, crew members and residents have participated fully in this research effort. Throughout the project they were helpful, insightful and gracious, and we owe them enormous gratitude. Special thanks and appreciation go to Dicky Schroder, Jerry Parisien and Todd Chase.

References
