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Abstract:
This study performed detailed thermal and moisture measurements in two homes in Fresno and Clovis, California with sealed attics insulated with glass fiber insulation to determine moisture performance in inland California climates. Data were recorded once every minute for more than a year in each home to allow detailed observation of time-varying moisture and thermal conditions. Moisture measurements were taken at multiple locations in each attic and included wood moisture, surface condensation and surface relative humidity. The results showed that there are strong solar-driven diurnal cycles in attic wood and air moisture content, as well as longer-term seasonal and annual variations. Mold growth was observed on the North roof deck in one of the two homes even in this sunny dry climate with attics built in compliance with California building codes that specifically address sealed and insulated attics with vapor-permeable insulation. We investigated moisture stratification in the attic and found that, although there is stratification during sunny daytime hours, this was not when wood moisture content, surface humidity or surface condensation are high. Therefore, other moisture transport mechanisms are acting to increase moisture levels near the roof peak. Our measurements also showed that the attic with the highest measured moisture levels did not have any mold growth, while mold was visually observed in the attic whose measurements indicted little or no concern, indicating that the state-of-the-art in moisture measurement and mold growth prediction in building assemblies may be insufficient.

Introduction

In this study we have monitored the thermal and moisture performance of two new sealed and insulated attics in the Fresno, CA region (CEC CZ 13; U.S. DOE CZ 3B) for more than a year. These attics were manually air sealed at the sheathing using canned foam sealant, and they were insulated solely with R38 fiberglass batts, held against the roof sheathing by support wires. The attic floor was gypsum bard and there were no deliberate vents installed between the house and the attic. Field testing showed that the attic floor leakage was about 1000 cfm (470 L/s) at 50 Pa. The homes are of wood frame slab-on-grade construction with the ducts, air handler and gas furnace located inside sealed and insulated attics. Both were located in new housing developments with neighboring homes but no mature trees. Monitoring of the occupied homes began in Fresno in late summer of 2016 and in Clovis in mid-June of 2017. Monitoring continued through Spring 2018. The Fresno home exceeds California Title 24 energy performance requirements by 30%, while the Clovis home is designed as a zero-energy home.

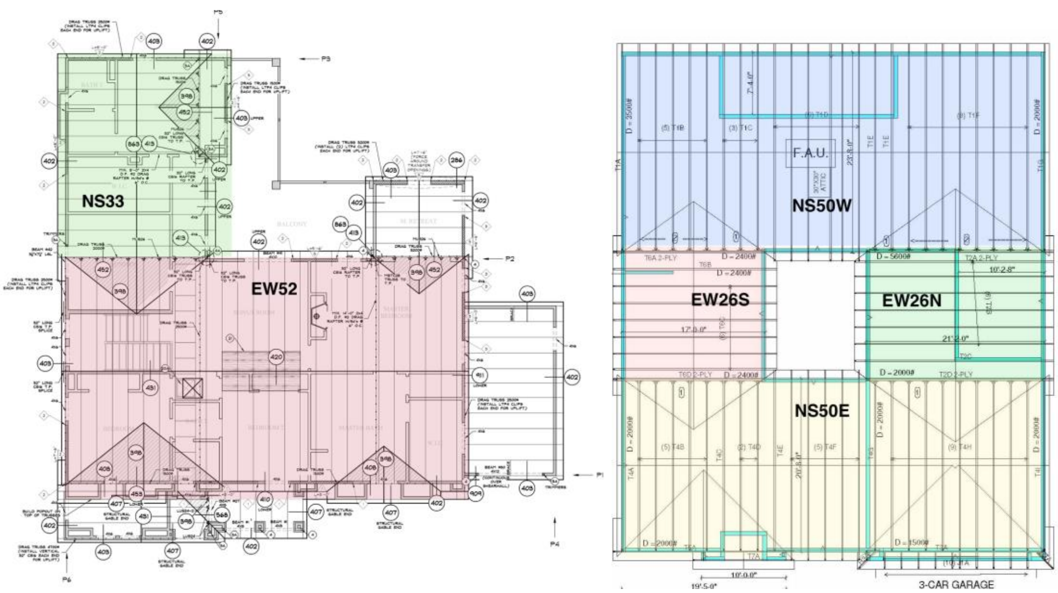

Figure 1. Plan view of the test homes: Clovis on the right and Fresno on the left

The Fresno home is a two-story residence with conditioned floor area (CFA) of 3,605 ft^2 (335 m^2), while the Clovis home is a smaller single-story residence with CFA of 2,146 ft^2 (199 m^2). The single-story Clovis home is roughly a square that surrounds a small interior courtyard and has four attic volumes connected by modest pathways of 1-2 ft^2 (0.1 to 0.2 m^2). The Fresno home is somewhat more traditional, with a basic L-shape and two main conditioned attic volumes—one with East-West orientation (and North-South oriented sloped roof surface) and another with North-South orientation (and East-West sloped roof orientations). Both homes have roofs sloped at 4:12 or 5:12 with OSB sheathing covered by building paper. The roofs are clad with medium-grey colored concrete roof tiles supported by horizontal battens (1.5” depth) with initial laboratory measured albedo of 0.12. These tiles are typical of new California construction. Figure 1 shows plan views of the two homes.

For the long-term monitoring, temperature sensors were arrayed at the eave, mid-span and ridge locations on the North- and South-facing roof pitches of the main attic volume. At each location, the temperature was measured at the attic air-insulation interface, mid-depth in the insulation, and at the insulation-sheathing interface. A temperature stratification tree was set up in the attic air volume, and a separate stratification tree of HOBO T/RH data loggers was also installed to assess moisture gradients in the attic air. Wood moisture probes were installed in the roof sheathing at each location (eave, mid-span and ridge) and orientation, as well as in the general attic framing. Relative humidity probes were installed mid-height in the attic air volume and at roof ridge locations. Surface condensation sensors were installed at the insulation-sheathing interface at the roof ridge for each orientation. More details of the monitoring hardware and data acquisition can be found in Less et al. (2018).

Results

Temperatures. The attic temperatures showed significant solar radiation effects. The Fresno attic was typically 2°C (3.6°F) warmer than the house during summer afternoons and 1°C (1.8°F) colder during winter mornings , averaging 0.8°C (1.4°C) warmer annually. The Clovis attic typically 7°C (12.6°F) warmer than the house during summer afternoons and 3°C (5.4°F) colder during winter mornings, averaging about 2°C (3.6°F) warmer annually. The greater differences for the Clovis house are likely because a substantial part of the attic was over unconditioned space (mainly the garage) and the small geometry of the monitored attic space with a higher surface area-to-volume ratio. At night and in winter there was little temperature stratification in the attic air. However, in the afternoon of summer months the attic air near the peak was about 10°C (18°F) hotter than air near the attic floor. The measured roof sheathing surface temperatures were typically warmest at the ridge, then mid-span and coldest at the eaves. Yet, moisture problems in sealed attics commonly occur at the ridge, which in our measurements, was the warmest location along the roof deck.

Relative Humidity (RH). The RH was measured at the ridge blocking on the South (EW52 Fresno), East (NS33 Fresno) and North (EW26N Clovis) exposures, and all other surface RH values were derived using the measured air humidity ratio and the relevant surface temperatures. The living space RH varied roughly between 30 and 60% RH in the Fresno test home, and between 30 and 50% in the Clovis home. As shown in Figure 2, the attic and living space air RH were similar in the Fresno test home. The Clovis test home was occupied in late September of 2017, and subsequently the attic and living space RH align. These measurements are consistent with the notion that the living and attic volumes are well mixed and within the same thermal and air-flow related pressure boudaries, i.e., the air has similar moisture contents, but RH varies somewhat by temperature. The peak sheathing locations have much more variable relative humidity, due to their fluctuations in temperature. As expected, the surface RH rises during the winter in all test attics as the sheathing gets cold. At the ridge sheathing locations, the daily average surface RH is in the 60-80% range for East and West orientations, 70-85% range for South, and 80-100% for the North orientations.

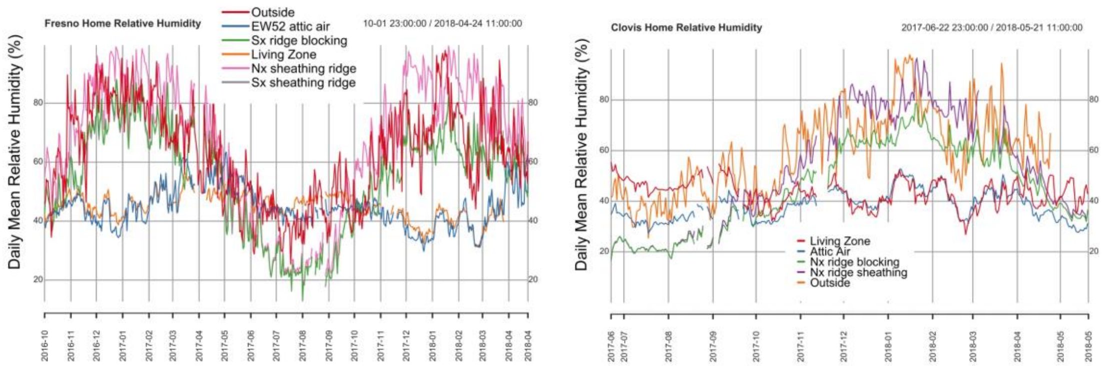

Figure 2. Daily average relative humidity over the monitoring period

Former ASHRAE 160 Surface RH Criteria. Prior to introduction of the mold index in ASHRAE 160, an assembly failed if the 30-day running average RH exceeded 80% while the 30-day running average surface temperature was between 5 and 40°C (41 and 104°F). The 30-day running average surface RH for the ridge sheathing locations, along with their hourly values are shown in Figure 3. The North ridge sheathing location failed the former ASHRAE 160 criteria (>80% RH) in both test homes, for roughly 4 months each winter in the Fresno home, and 1 month in the winter in the Clovis home.

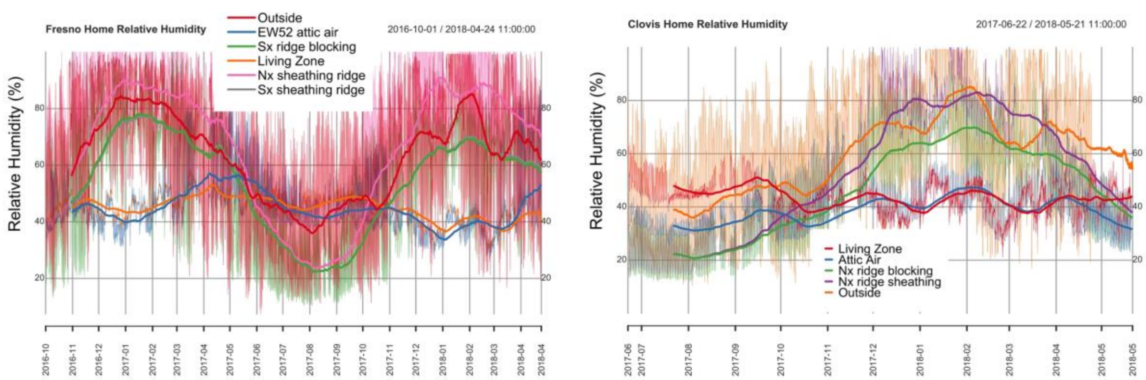

Figure 3. Former ASHRAE 160 moisture criteria: 30 day running average (and hourly values) of RH

Current ASHRAE 160 Mold Index. The mold index is the new performance critiera in ASHRAE 160, and an assembly fails if the mold index exceeds 3. The mold index uses the same 80% RH threshold for mold growth, but it couples surface temperature and RH to produce time-dependent wetting and drying impacts on mold growth risk, as well as material sensitivity classes. The mold index values are shown for each test home in Figure 4. Insulated roof deck assemblies passed this criteria in each test home. In Fresno, the maximum for this 565-day period was 1.97 in the North ridge sheathing location, which indicates several local mold growth colonies on the surface visible only under microscope. All other locations peaked below 0.1. The Clovis house shows much lower mold index values, with the North ridge sheathing peaking at 0.25 during the first winter of occupancy, indicating a very low probability for mold growth. These results correspond to those reported elsewhere (summarized in Less et al. (2016)), that moisture issues are most common at the North, ridge sheathing. The results show seasonal cyclic wetting and drying, with wintertime wetting periods where mold index increases due to a cold roof surface from November through April, and consistent summer dry periods where the mold index falls. Additional calculations in the companion simulation effort (see Less et al. (2018)), which cover 4-year performance periods, show that this pattern will dampen out at a stable level, but we cannot say if that level will be above or below the ASHRAE 160 threshold of 3.

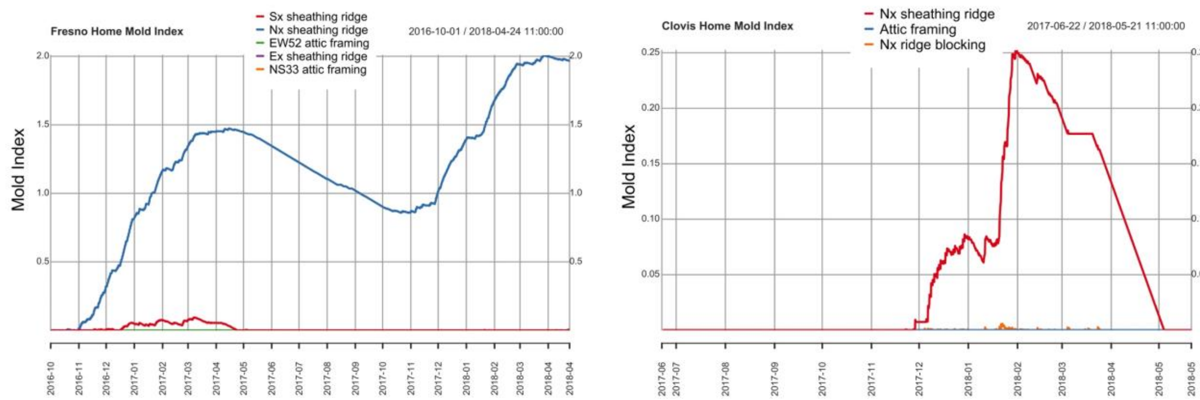

Figure 4. Mold index for the Fresno and Clovis homes calculated using ASHRAE 160.

Surface Condensation. The only measured surface condensation in either test home occurred at the North ridge sheathing location in the Fresno test home. According to the condensation sensors, there was liquid water present at the North ridge sheathing for 30% of annual hours. On an annual rolling basis, the fraction varied from 30 to 43% of annual hours. We suspect the sensor may have drifted, as the second monitored winter was markedly drier (based on ambient weather and other attic measurements), yet showed increasing hours with liquid water present.

As an additional check on the condensation sensors, we calculated the dew point temperature at each roof deck ridge location and assessed when the corresponding dry bulb temperature was below the dew point. Again, the North ridge roof deck in the Fresno home was the only location that showed substantial time below the dew point temperature, and when annualized, the fraction of hours with condensation potential ranged between 7.5 and 9%, with no marked trend with time (i.e., it did not increase from the first to the second winter). This dew point method estimated 0.6% of monitored hours (41 out of 6,982 hours) with condensation potential at the Clovis North ridge sheathing. Notably, liquid water can be present on a surface that is above the dew point temperature of the surrounding air, because of liquid water previously deposited on the surface that has not yet been evaporated.

Wood Moisture Content (WMC). Daily mean wood moisture contents are shown in Figure 5. Both homes show a pattern of increased surface WMC during the heating season, with very dry conditions during the summer season. After relatively high surface moisture levels were observed at the North ridge sheathing location in the winter of 2016/2017, we installed two additional North ridge WMC pin sets, but with insulation guarding them from the surface moisture, to depths between 0.35 and 0.45 cm (0.14 and 0.18 in.) into the Oriented Strand Board (OSB) sheathing. These deep WMC pins measured peaked at 10.2%, while the North ridge surface reached 16%. The North sheathing at the eave registered a maximum value of 12.5%, while all other locations remained below 10% in the second winter. Overall, the wood moisture measurements in both test homes are mostly within safe conditions. 28% is the common threshold for wood rot and decay organisms, and neither home ever reached this level.

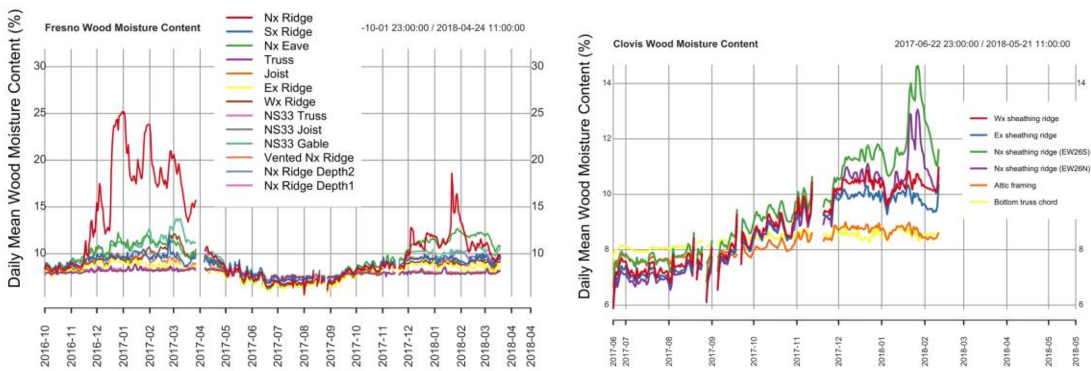

Figure 5. Wood moisture content

Moisture Stratification. Figure 6 shows a substantial vertical moisture gradient established from the attic floor to the ridge during the peak solar gain daytime hours. Moisture stratification in the attic air volume disappears during nighttime hours, when the gradient is nearly zero, and the attic air appears well-mixed from a moisture standpoint. The patterns of stratification vary substantially by season, depending on solar gains and length of day. During the heating season, vertical moisture stratification is evident, but only from roughly from 2 pm to 5 pm (from roughly 10 am to 6 pm in the cooling season). Moisture problems tend to occur during the heating season, yet these results show that the daytime moisture gradient in the heating season averages at most 200-300 Pa (0.8-1.2 in. water) from ridge to attic floor, and it lasts for only a few hours during the warmest part of the day. It appears unlikely that vertical moisture stratification in the attic air volume causes moisture accumulation at the roof ridge.

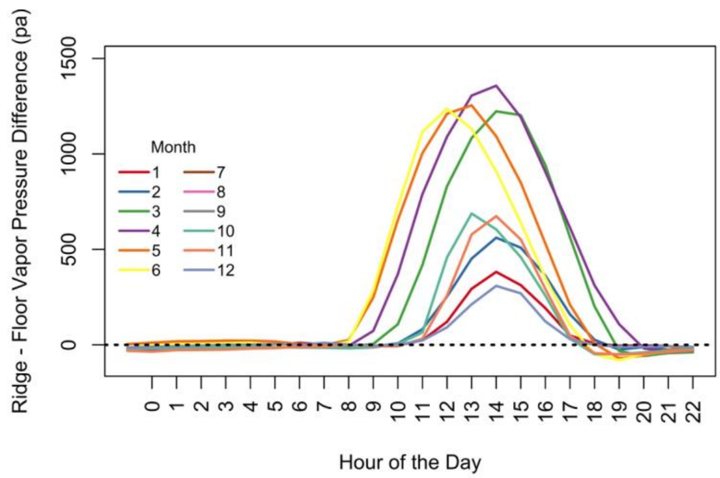

Figure 6. Vapour stratification in the Fresno attic

One explanation for the moisture gradient could be the result of attic geometry. Going from the attic floor to the ridge, the surface area of OSB sheathing remains constant (same moisture source), but the adjacent air volume gets much smaller. This is further worsened by higher roof deck temperatures near the ridge on sunny, clear days, which would increase the water vapor emission rate from the roof deck into the small air volume at the roof ridge. This leads to higher moisture contents in the air at the ridge. The elevated vapor pressure at the ridge could just be moisture emitted at the ridge and re-absorbed at the ridge, with no (or little) net-transport to or from other locations in the attic. This vertical moisture gradient during solar gain periods would lead to a corresponding gradient in equilibrium wood moisture content – with high wood moisture at the ridge. However, this explanation may be insufficient because the higher ridge wood moisture contents were observed in cold winter months and/or at night time, when the vertical gradient is small or non-existent. It may be that the winter daytime gradients are sufficient to sustain a higher average wood moisture content and other mechanismas are at play—such as the ping-pong suggested by Ueno & Lstiburek (2015). Another possibility is that a vertical moisture gradient exists near the roof deck at times when higher wood moisture contents are observed, but is not reflected in the attic air volume. A boundary layer of moisture-laden air may be trapped near the OSB surface, which is allowed to travel vertically up the roof slope, due to small gaps between the insulation and OSB or through the batt itself. We have no evidence for this boundary-layer explanation and additional experiements are required to investigate this further.

Vapor Pressures. Time-series of the outside, living zone, attic ridge and attic air vapor pressures in the EW52 Fresno attic are shown in Figure 7 for summer and winter. The vapor pressure patterns are strongly diurnal, driven by solar radiation during daytime hours, which increases the vapor pressure at the roof deck, as well as in the attic air and in the living space. We see the so-called “ping-pong” effect in the Fresno attic, where moisture is driven from the roof deck into the attic, and is then reabsorbed at nighttime (ridge vapor pressure drops below attic and living space air). Hourly vapor pressure patterns in the Clovis test home were similar to those measured in the Fresno test home.

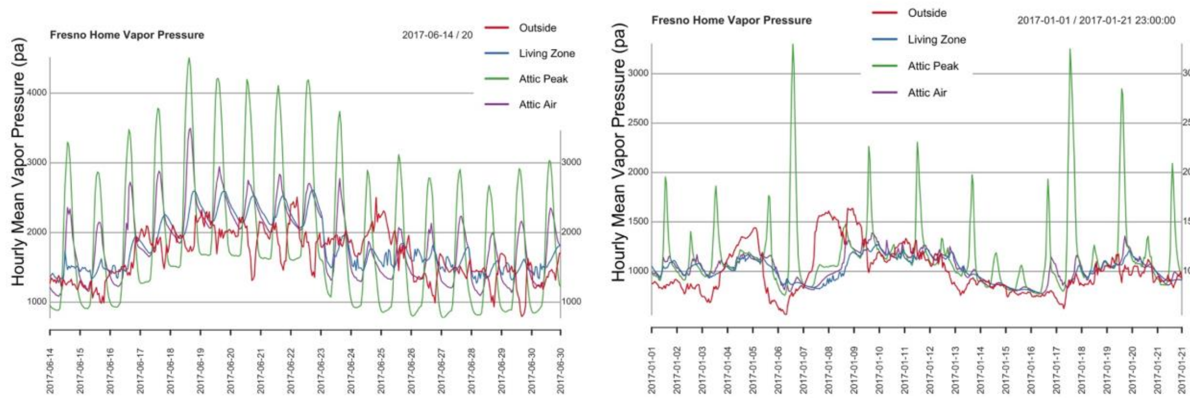

Figure 7. Vapour pressure time variation in the Fresno attic for summer (left) and winter (right)

To estimate the net-effect of these strong diurnal cycles of vapor pressure, the rolling monthly average vapor pressure is shown for the whole monitoring period in Figure 8. In both homes, the attic air and living space air are well-coupled in terms of vapor pressure, except during the Spring season, when the attic has a higher vapor pressure than the house (roughly 200-300 Pa). We hypothesize that this is the result of moisture mass stored in the OSB roof deck during the cold winter, which is then re-emitted into the attic air as conditions warm in spring. All indoor locations register their highest vapor pressure levels during springtime, including the living space, attic air and roof deck. In the Clovis home, the living space is marginally more humid than the attic space above, suggesting the living space could be a source of moisture for the attic. The ridge sheathing has the consistently highest vapor pressure throughout the year, despite very dry wood moisture conditions during the summer under high solar gain conditions. The outside air has lower mean vapor pressure during all months of the monitoring period, except in August of 2017, when it roughly equals the living space and attic vapor pressures. This is consistent with the addition of moisture to the living space by occupant activities and building materials, which increases absolute humidity in conditioned space above outdoor ambient levels. Outside air is near-continuous source of drying potential for this home and attic. Given these measured trends between the attic and living space, we expect that intentional mixing of the living space and attic to have little impact on moisture levels in either space, except possibly during spring, when mixing could facilitate drying of the attic air.

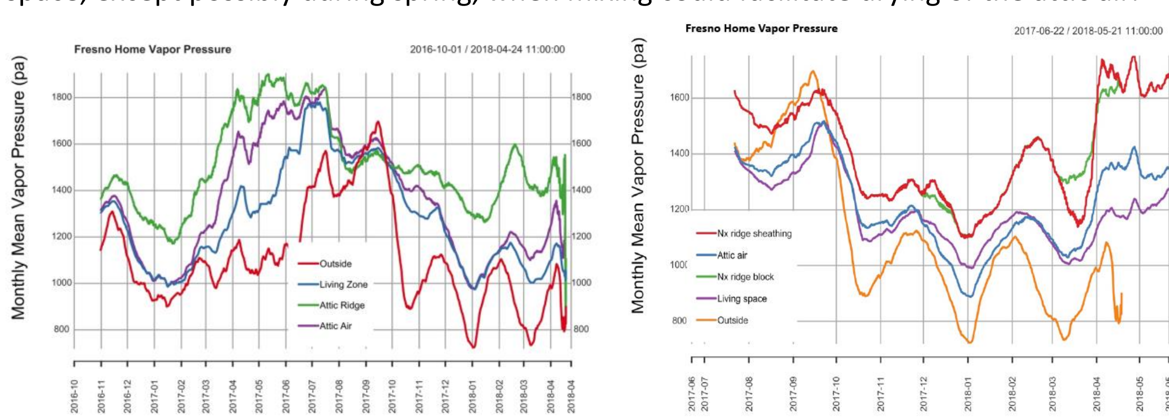

Figure 8. Rolling monthly average vapour pressures in the Fresno (left) and Clovis (right) test homes.

Visual Inspection. A visual inspection of the monitored areas was performed during removal of monitoring equipment. In the Fresno test home, no evidence of mold growth was observed, though we did observe evidence of prior condensation near the ridge on the North-sloped roof deck, including rusted roof fasteners, rusted wire mesh netting over some sensors, and raised grain on the OSB roof deck surface. In the Clovis test home, we found visual mold growth on the North-sloped roof deck and the top chord of the roof truss (see Figure 9). There were also rusted fasteners and raised grain on the OSB. The suspected mold was later confirmed by a 3rd party testing company, and mold was also found in the other North-sloped roof surface in an attic volume that was over another part of the home. The other orientations were free of visual mold though we did observe some very limited rust formation on roof fasteners in the East and West sloped roof ridges. No odor was discernable in the attic.

This finding was surprising given the moisture measurement results presented in prior sections. The Fresno test home was free of visual mold, yet it had substantial surface condensation, a moderately high mold index, elevated wood moisture content nearing rot organism thresholds, and elevated surface RH that failed former ASRHAE 160 critera for roughly 4 consecutive months each winter. The Clovis home was drier, with no measured condensation, a mold index value indicating no mold growth at even microscopic levels, and wood moisture content that peaked for a few hours at the long-term mold growth threshold of 16%. Yet, visible mold was observed broadly across the North roof slope in the Clovis home. We are aware of one other research project that has identified mold growth in a sealed attic where the mold index predicted mold-free conditions (Ueno & Lstiburek, 2018). Other mold researchers have specifically identified scenarios when the mold index model can dramatically underpredict mold risk (Vereecken, Vanoirbeek, & Roels, 2015).

Conclusions

North-facing roof decks were susceptible to mold and other moisture issues even in a relatively mild California climate when complying with California building code requirements intended to ensure adequate moisture performance. Note that it is possible that these effects could be different with roof coverings with lower solar absorbtion that would reduce the solar driven temperature differences. This work makes clear that preventive measures are needed to reduce the risk of mold growth in sealed and insulated attics using only fibrous insulation. Current measurements of surface condensation, wood moisture content and humidity are not sufficient to reliably predict moisture issues such as mold growth. In addition, current mold growth assessment tools need improvement. In this study they predicted mold issues where there were non observed and did not predict mold issues for an attic that was moldy. Better moisture control strategies are needed in building codes if air permeable insulation is used in this application.

Figure 9. Clovis test home, photo of mold growth on North-sloped OSB roof deck (right side)

We do not have a good explanation for why wood moisture content is higher at the ridge based on our stratification measurements. Stratification does not appear to be a good candidate, because during times of moisture accumulation (nighttime and during winter) there is little to no stratification. Further study is needed to fully understand the moisture dynamics: for example, the coldest part of the roof deck was at the eaves, and yet this location did not display condensation or increase in wood moisture content. There may also be implications for using cool-roof materials, air flow/moisture transport underneath the roofing tile, and the use of attic moisture venting strategies. These remain areas for further research.

References

Less, B., Walker, I., & Levinson, R. 2016. *A Literature Review of Sealed and Insulated Attics—Thermal, Moisture and Energy Performance* (No. LBNL--1006493). https://doi.org/10.2172/1340304

Less, B., Walker, I. , Slack, J., Rainer, L. and Levinson, R. 2018. *Sealed and Insulated Attic Hygrothermal Performance in New California Homes Using Vapor and Air-Permeable Insulation-Field Study and Simulation.* California Energy Commission. EPC-14-012

Vereecken, E., Vanoirbeek, K., & Roels, S. (2015). Towards a more thoughtful use of mould prediction models: A critical view on experimental mould growth research. *Journal of Building Physics*, *39*(2), 102–123. https://doi.org/10.1177/1744259115588718

Ueno, K., & Lstiburek, J. (2018, September). *Unvented Roof Without Spray Foam: The Latest Building America Research*. Presented at the 13th Annual North American Passive House Conference, Boston, MA. Retrieved from http://www.phius.org/NAPHC2018/2018-09-14%20Ueno%20NAPHC%20Unvented%20Roofs.pdf

Ueno, K., & Lstiburek, J. (2015). *Field Testing Unvented Roofs with Asphalt Shingles in Cold and Hot-Humid Climates* (Building America Report No. BA-1409). Westford, MA: Building Science Corporation. Retrieved from http://buildingscience.com/documents/ba-1409-field-testing-unvented-roofs-asphalt-shingles-cold-and-hot-humid-climates