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Authors

Less, Brennan
Walker, Iain
Levinson, Ronnen

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A Literature Review of Sealed and Insulated Attics—Thermal, Moisture and Energy Performance

Brennan Less, Iain Walker & Ronnen Levinson

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Disclaimer

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Abstract

In this literature review and analysis, we focus on the thermal, moisture and energy performance of sealed and insulated attics in California climates.

Thermal. Sealed and insulated attics are expected to maintain attic air temperatures that are similar to those in the house within +/- 10°F. Thermal stress on the assembly, namely high shingle and sheathing temperatures, are of minimal concern. In the past, many sealed and insulated attics were constructed with insufficient insulation levels (~R-20) and with too much air leakage to outside, leading to poor thermal performance. To ensure high performance, sealed and insulated attics in new California homes should be insulated at levels at least equivalent to the flat ceiling requirements in the code, and attic envelopes and ducts should be airtight. We expect that duct systems in well-constructed sealed and insulated attics should have less than 2% HVAC system leakage to outside.

Moisture. Moisture risk in sealed and insulated California attics will increase with colder climate regions and more humid outside air in marine zones. Risk is considered low in the hot-dry, highly populated regions of the state, where most new home construction occurs. Indoor humidity levels should be controlled by following code requirements for continuous whole-house ventilation and local exhaust. Pending development of further guidance, we recommend that the air impermeable insulation requirements of the International Residential Code (2012) be used, as they vary with IECC climate region and roof finish.

Energy. Sealed and insulated attics provide energy benefits only if HVAC equipment is located in the attic volume, and the benefits depend strongly on the insulation and airtightness of the attic and ducts. Existing homes with leaky, uninsulated ducts in the attic should have major savings. When compared with modern, airtight duct systems in a vented attic, sealed and insulated attics in California may still provide substantial benefit. Energy performance is expected to be roughly equivalent between sealed and insulated attics and prescriptive advanced roof/attic options in Title 24 2016. System performance can also be expected to improve, such as pull down time, performance at peak load, etc. We expect benefits to be reduced for all advanced roof/attic approaches, relative to a traditional vented attic, as duct system leakage is reduced close to 0. The most recent assessments, comparing advanced roof/attic assemblies to code compliant vented attics suggest average 13% TDV energy savings, with substantial variation by climate zone (more savings in more extreme climates). Similar 6-11% reductions in seasonally adjusted HVAC duct thermal losses have been measured in a small subset of such California homes using the ducts in conditioned space approach.

Given the limited nature of energy and moisture monitoring in sealed and insulated attic homes, there is crucial need for long-term data and advanced modeling of these approaches in the California new and existing home contexts.

Executive Summary

This literature review document is intended to summarize the state-of-the-science for sealed and insulated residential attics across the United States (U.S.). This is in support of California Energy Commission-funded (CEC) research into sealed and insulated attic performance in new California (CA), code-compliant homes. Results will be used to support development of code requirements for inclusion in the Title 24 Building Energy Codes (T24). This review covers the following topics, as they relate to sealed and insulated attics: overall advantages/disadvantages, attic simulation tools, existing code requirements, costs, envelope and HVAC duct airtightness, thermal performance, moisture performance, energy performance and California considerations.

This executive summary presents findings from a detailed review of the residential sealed and insulated attics literature. A total of 99 papers and reports were reviewed from the early 1990s to the present. This section contains general conclusions and insights; readers interested in references for the papers that were reviewed, or who want further details, may read the applicable sections in the attached report.

The following potential ***advantages*** are attributed to sealed and insulated attic designs.

- Placement of a home's primary air and thermal boundaries at the sloped roof surface in large part brings the attic (and any HVAC equipment located in the attic) into conditioned space, even when no direct conditioning is provided. This leads to small temperature differences between the attic and the occupied space of the home. Relative to traditional vented attics, sealed and insulated attic air temperatures are generally warmer during winter and cooler during summer.
- HVAC loads are often reduced for systems located in the attic, due to the tight coupling of house and attic air temperatures.
- Thermal losses from the HVAC system, due to air leakage for example, are recaptured in the home's conditioned space. As a result, inefficiencies in the HVAC system (e.g., low refrigerant charge, poor airflow design, and duct air leakage) have less impact on whole house performance.
- As a result of improved thermal performance, air conditioner capacity may be reduced by approximately 0.5 refrigeration tons (6.3 kJ) for a typical sized home.
- Reduces peak demand during afternoon summer cooling periods.
- Reduces potential for condensation to occur on HVAC ducts in cooling operation.
- Placing ducts in conditioned space can help to eliminate air pressure differences throughout the home that are induced by HVAC operation.

- Moves primary air and thermal barriers to the roof deck, which permits complex ceiling designs, ceiling height changes and numerous ceiling penetrations from lighting and services.
- Some sealed and insulated attic designs can easily accommodate complex roof plans, which are very difficult to vent properly.
- Eliminates wind-driven snow in cold climates, wind-driven rain penetration in coastal climates, and wind-driven embers from wild fires.
- A sealed and insulated, conditioned attic provides additional living and storage space.

The following potential ***disadvantages*** are attributed to sealed and insulated attic designs.

- Increases roof surface area for air leakage and heat loss/gain (combined sloped roof and gable surface area exceeds attic floor area), and increases material costs for insulation.
- Increases temperature difference across the thermal boundary during cooling hours (shingles-to-attic-air vs. attic-air-to-house).
- Sealed and insulated attics that do not achieve sloped roof R-values equivalent to those specified for flat ceilings may offer less thermal resistance and little or no energy benefits, even when insulated with spray polyurethane foam (SPF) insulation.
- It may be substantially more difficult to install insulation at the structural roof sheathing than on the flat ceiling.
- Increases roof shingle and structural sheathing temperatures.
- Any gas appliances located in a sealed and insulated attic must use sealed combustion, because they lack combustion and

ventilation air paths to outside.

- Placing insulation at the roof deck can cool the roof sheathing in winter, which might lead to condensation and moisture accumulation in the roof assembly. In summer, roof sheathing and cladding temperatures are expected to increase.
- Sealed and insulated attics may cost more to build than vented attics.
- Exposed and untreated SPF insulation in sealed and insulated attics may violate fire provisions in the building code.

Simulation tools currently used in assessments of residential attics fall under several broad types: (1) assembly-based tools, (2) full attic models, and (3) house-attic system models. Many studies reviewed required multiple tools to assess attic thermal and moisture performance. All tools face difficulties predicting the complex thermal and moisture dynamics of residential attics.

Current ***building code requirements*** that apply to high performance residential attics include: (1) provisions in the 2016 California Title 24 residential building code (T24), including mandatory and prescriptive options for high performance attics and HVAC systems; (2) requirements in the 2012 International Residential Code (IRC) for use of air impermeable insulation in sealed and insulated roof assemblies, depending on the climate zone and roof finish; (3) requirements in the 2012 IRC for inclusion of a class II vapor retarder in International Energy Conservation Code (IECC) climate zone (CZ) 5 and above; and (4) fire safety requirements in the 2012 IRC for use of ignition barriers, including intumescent paint[1], sheet rock or the like.

The ***cost of sealed and insulated attic construction*** has not been widely reported in research or trade literatures, though what is available suggests that the price premium for a new single-family home in the United States (U.S.) is on the order of US$700 to $3,000, averaging roughly $1,000 per home (from $0.60 to $1.40 per ft^2 of attic floor area). This varies with the size of the home, number of stories, insulation materials used, and the ability to absorb or distribute one-time information/design costs. The cost premium for sealed and insulated attic construction is comparable to that of other techniques that place ducts in the conditioned space, such as attic chases and dropped-ceilings plenums. Retrofit costs in existing homes may be substantially higher.

Building envelope and duct airtightness in sealed and insulated attic homes.

- Attic airtightness criteria are not included in either the 2012 IRC, or in the U.S. Department of Energy (DOE) Building America Measure Guideline for Sealed and insulated Attic Insulation. We are unaware of any other programs that specify attic airtightness requirements.
- Unless explicitly assessing construction quality (e.g., leakage per square foot of surface area), then airtightness testing should be performed with the attic access in its typical position (i.e., closed).
- Most sealed and insulated attics remain at least somewhat leaky to both the house and to outside; on average 52% of whole-house leakage area was located in the sealed and insulated attic surfaces (compare to 51% through the ceiling in conventional California attics).
- Sealed and insulated attics in modern, new California homes (compliant with 2013 Title 24 requirements) may be substantially more airtight than older homes described in earlier research, with median attic air leakage to outside of 246 cfm_{50} (newer homes) vs. 921 cfm_{50} (older homes).
- Sealed and insulated attics are generally somewhat leakier than the houses to which they are attached, but attics are still more coupled to the house than to outside, in terms of heat and mass transfer.
- Sealed and insulated attics insulated with fibrous insulation can achieve airtightness levels comparable to those in attics insulated with SPF.

[1] Intumescent coatings are used as a passive means of fire protection in a variety of applications. They generally function by releasing water vapor, which has a cooling effect, and they also leave a charred layer behind that provides additional thermal resistance, which slows flame spread into the underlying material.

- Detailed measurements in a single housing development of modern new California homes suggest that duct systems in sealed and insulated attics have very low air leakage to outside (averaging 1% of total system airflow, or 18 cfm), but substantial leakage still occurs within the envelope (median of 8%, 106 cfm). HVAC systems documented in older research were located inside leakier attics, and as a result, 55% of total duct leakage was to outside (32 cfm to outside on average).
- The airtightness of any duct system located in a sealed and insulated attic should be tested. For the purposes of energy calculations, leakage-to-outside tests should be used, which ignore duct leakage that occurs within conditioned space.
- Common locations for air barrier defects in sealed and insulated attics include (1) plumbing penetrations, (2) framing intersections, (3) roof and wall intersections, and (4) vent locations in existing homes. Common defects include foam delamination, as well as non-existent or inconsistent application of sealants (e.g., caulk, SPF or gaskets).

Thermal performance of sealed and insulated attics:

- Past field measurements suggest that temperatures in sealed and insulated attic volumes are well coupled to the house volume, an effect seen whether the ceiling plane is airtight or leaky. We expect even tighter coupling of the attic and house volumes under two conditions: (1) with direct conditioning (i.e., using intentional supply of heated or cooled air to the attic volume), and (2) as sealed and insulated attics become more thermally insulated and airtight (compared with older sealed and insulated attics, which were often leaky and inadequately insulated).
- It is extremely rare for the sealed and insulated attic volumes to be more than 10°F (5.6°C) above or below the house temperature in hot-dry climate regions.
- Sealed and insulated attics are generally warmer than the house during summer and cooler than the house during winter.
- Peak roofing shingle temperatures (upwards of 180°F (82°C)) can be approximately 20°F (11.2°C) higher over sealed and insulated attics than over vented attics, but typical differences (sealed and insulated – vented) are 3 to 7°F (1.7 to 3.9°C), and long-term average differences are very small (<1°F (0.5°C)). Peak roof sheathing temperatures are also elevated in sealed and insulated attics, typically by 16 to 17°F (9 to 9.5°C).
- The solar properties, presence of above-sheathing ventilation, and thermal mass of roof assemblies strongly influence attic/roof thermal performance. The effects of these parameters on attic air temperature and HVAC system energy use are often greater than those predicted or observed for sealed and insulated attic approaches. The benefits of a sealed and insulated attic strategy are expected to increase when coupled with cool roof and other advanced strategies (e.g., above-sheathing ventilation and thermal mass).

Moisture performance of sealed and insulated attics:

- The primary moisture concern in residential attics is the accumulation of moisture in wood building assemblies, which are subject to biological growth, deterioration and failure under certain conditions. Concern is highest at the underside of the structural roof sheathing, where moist indoor air can contact the cold sheathing surface. This sheathing surface temperature is called the 'first condensing surface temperature', and preferably it should be kept above the dew point temperature of the attic air. Sheathing surface temperatures decrease due to cold outside temperatures, as well as due to radiative heat loss to the night sky. Greater thermal resistance in the roof assembly also leads to lower sheathing temperatures (e.g., R-60 fiberglass batts are more risky than R-19 batts).
- The following factors increase moisture risk at roof sheathing surfaces over sealed and insulated attics:
    - Increased indoor or outdoor humidity
    - Lower outdoor winter temperatures and higher levels of night sky radiation
    - North-facing roof slopes
    - Proximity to the roof peak
    - Use of air permeable insulation
    - Use of cool roof surfaces or radiant barriers
    - Increasing vapor permeability of insulation (maybe)
- To reduce moisture risk, the first priority should be elimination of paths for bulk water intrusion from outside. Once bulk water is controlled, the primary means for controlling moisture levels in sealed and insulated attic roof assemblies are: (1) controlling the first condensing surface temperature, typically through use of continuous exterior insulation or air impermeable insulation in the roof rafter assembly; or (2) control of indoor moisture levels, typically through moisture removal by continuous whole house and intermittent local exhaust ventilation. Supplemental dehumidification or direct conditioning[2] of the sealed and insulated attic volume may be necessary in some cases, generally in hot-humid climates. Other proposed methods to reduce moisture risk include use of vapor permeable diffusion caps at roof peaks, enhanced roof deck ventilation and increased mixing of attic and house air volumes.
- Sealed and insulated attic/roof assemblies should strike a balance between their ability to limit wetting and to allow drying. The ability of an assembly to safely store and redistribute moisture is also important.
- Assessments of sealed and insulated attic assemblies at the design stage can be performed using hygrothermal analysis tools (i.e., WUFI), along with the criteria in ASHRAE Standard 160. The standard stipulates that to reduce the

[2] Air leakage from ducts located in sealed and insulated attics already provides some level of direct conditioning, albeit inadvertent.

risk of mold growth, 30-day running average surface relative humidity should be below 80% when 30-day running average temperature is between 5 and 40C°. Time-dependent mold index modeling and thresholds are likely to replace this simple criterion in the near future.

- Total roof failures that require large-scale interventions (e.g., full re-roofing and sheathing replacement required) are rare, with the only example seen in this literature review involving installation of closed cell spray polyurethane foam (ccSPF) over wet roof sheathing.
- Field observations of problematic moisture conditions in sealed and insulated attics (e.g., condensation and dripping moisture) are more common. These have been reported in cold, mixed- and hot-humid climate zones. One example was reported for a California home (unknown location). These moisture issues are far and away most common in cases where fibrous insulation is used, generally near the roof peak.
- The dynamics of time-varying wood moisture content (MC)[3] and temperature determine moisture risk. Risk varies across different materials, with untreated lumber generally most susceptible to damage. The longer an assembly is at high MC (i.e., >30%), the more likely damage is to occur. Typically mold growth is inhibited at surface relative humidities below 80%. The risk of mold growth on wood also varies with temperature. Cold temperatures inhibit biological growth, making mold growth during cold winters unlikely, even if moisture accumulation occurs. Drying of seasonally stored moisture should proceed quickly to reduce risk of mold growth, because rising temperatures in the spring bring about conditions amenable to mold growth. Short periods of high MC are acceptable, as long as drying proceeds quickly, and there is no net-accumulation of moisture year-on-year.
- Moisture conditions in the attic air, attic framing and roof assembly can vary substantially on daily and seasonal bases. For example, attic air humidity commonly approaches saturation (i.e., 100% relative humidity) during summer afternoons in hot-humid regions, because solar gains drive moisture stored in the attic materials into the air, which is at a lower vapor pressure. The MC of materials in sealed and insulated roof systems can also vary widely on a seasonal basis (e.g., from 4 to 25%), making the time of any diagnostic measurements important.
- Moisture dynamics in sealed and insulated attics are different than those in vented attics. For example, peak attic air relative humidity is roughly coincident with peak solar irradiance in sealed and insulated attics, whereas vented attics experience the lowest air relative humidity at this time, due to elevated air temperatures.
- Based on long-term averages, house volumes and sealed and insulated attic volumes have similar moisture conditions.

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[3] Wood MC is represented as a mass-fraction value, and it is the ratio of the mass of water in a sample of wood versus the mass of the same sample after oven drying.

- Many in the field now consider at least partial direct conditioning of the sealed and insulated attic to be crucial, but this may already be provided by air leakage from the duct system.
- When using fibrous insulation, cellulose may provide some beneficial moisture protection, because: (1) it provides moisture storage and acts as a buffer, (2) it reduces air movement in the assembly, and (3) it contains borate preservatives.
- There is limited evidence that humidity levels are somewhat elevated in sealed and insulated attic homes, because the attic serves as a moisture source for the house. During humid periods, the attic stores rather than vents moisture, and this moisture is then released back to the conditioned volume when the driving forces reverse.
- Condensation on the exterior roof surface is an unlikely moisture source for sealed and insulated attic assemblies.
- Elevated indoor humidity in new, energy efficient homes may increase the moisture risk posed by sealed and insulated attics. This problem is greatest in assemblies that do not control condensing surface temperatures through use of exterior insulation or air impermeable cavity insulation.

Energy performance of sealed and insulated attics.

- Energy performance is highly dependent on several parameters, including the insulation levels provided on the roof surfaces (often less than that provided on vented attic ceilings); the presence of HVAC equipment in the attic; the presence of air leakage in the HVAC distribution system; and the roof assembly characteristics, such as roof solar absorptance and the presence or absence of a radiant barrier in the attic.
- Insulation levels on sloped roof surfaces above sealed and insulated attics (and on gable walls) should be similar to or greater than insulation levels on the floors of vented attics.
- Energy savings are only expected for sealed and insulated attics if they contain HVAC systems and ducts. Savings increase when ducts are leaky or poorly insulated.
- Very little field data exists on the energy performance of sealed and insulated attics. Short-term field tests suggest that cooling energy savings range from 6 to 20%, and heating savings range from 0 to 25% (depending on wind conditions). The presence of leaky ducts in the attic is the clear determinant of energy performance. In real-world tests (i.e., not controlled experiments), very little (if any) performance benefit has been reported for homes with airtight duct systems.
- Limited measurements of HVAC distribution efficiency (using calculation and reporting methods from ASHRAE Standard 152[4]) have been made in sealed

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[4] ASHRAE Standard 152 *Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems* provides estimates of the efficiency of thermal distribution systems under heating and cooling operation for use in estimates of energy consumption and/or

and insulated attics. Measurements in modern, new California homes (Title 24 2013) found 6-7% improvements in seasonal heating distribution efficiencies, and 8-11% improvements in seasonal cooling distribution efficiencies. Past measurements in poorly constructed (i.e., leaky and inadequately insulated) sealed and insulated attics found no distribution efficiency benefit relative to vented attics.

- In simulations, sealed and insulated attic performance varies considerably with climate zone, with greater absolute energy savings in climates with higher heating or cooling demand. Annual energy savings are at most 20% and more commonly 3-10%. As was indicated by field measurements, the presence of HVAC ducts in the attic and the level of duct leakage were consistently found to be very important factors in determining energy savings. Simulations show mixed results for airtight duct systems, with some research reporting meaningful savings. The most recent simulation assessments of new code-compliant California homes predict substantial average savings on the order of 13 to 18% for sealed and insulated attics, relative to traditional vented attic, code-compliant cases.
- Peak demand reductions are highly climate variable, and have been reported between 0 and 1 kW.
- Simulations in locations across the U.S. have consistently suggested that combining sealed and insulated attics with white roof coverings provides superior performance, though a heating season penalty will exist in most places. Annual energy cost and source energy savings are still evident, with the possible exception of the coldest locations, such as Minneapolis, where heating penalties and cooling benefits approximately cancel out.

In the ***California context***, builders and designers face myriad options for compliance with the upcoming 2016 Title 24 Energy Code. These include: (1) prescriptive path options, such as high performance vented attics (HPVA) and vented attics with ducts in conditioned space (DCS); as well as (2) performance path options, such as conventional vented attics and sealed and insulated attics. It is clear that the ability of sealed and insulated attics to reduce energy consumption depends on adequate insulation and envelope/duct airtightness. Sealed and insulated attics are commonly constructed using SPF insulation, which is expensive and is often installed to only minimum thicknesses (i.e., code minimum R-22 in CA T24 2016). Sealed and insulated designs in the state are needed to provide both lower installation cost and higher thermal resistance. We are investigating the energy and moisture performance of sealed and insulated attic assemblies built using only air permeable insulation throughout the state (as opposed to sealed and insulated assemblies that use SPF insulation in-whole or in-part).

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equipment sizing. Seasonal weather conditions are used for energy estimates and design weather conditions for equipment sizing. Calculations are based on measured parameters and factors including duct location, air leakage and insulation of ductwork.

Some key questions are:

- *What energy savings do we expect from sealed and insulated attics in new California homes built to 2013 or 2016 Title 24?*
    - Recent work in new California homes, funded by the California Energy Commission, suggests that substantial energy savings are available for sealed and insulated attics, relative to code-compliant vented attic homes. This has been predicted by simulations and supported by a single field study of duct system efficiency in vented and sealed and insulated attics. This work suggests that sealed and insulated attics are expected to yield annual whole-building energy budgets comparable to those obtained with advanced vented attics, such as those in the Title 24 2016 prescriptive packages. These approaches all have unique costs and benefits that builders/designers should weigh on a case-by-case basis.

- *What are the moisture-related risks of sealed and insulated roofs constructed with entirely air permeable insulation?*
    - Moisture risk is expected to be low in the most populated regions of the state, which in turn are where most new homes are built. Cold and marine locations are higher risk. Furthermore, a number of features of the current prescriptive requirements in the Title 24 energy code (i.e., cool roofs, radiant barriers, sealed/insulated ducts and ventilation cooling) may increase the risk of moisture accumulation and damage in sealed and insulated attics in California. When coupled with the general tendency for energy efficient homes to have higher indoor humidity, this leads to moderate risk levels in some California climates and contexts. We recommend control of indoor humidity through compliance with the code's mechanical ventilation requirements. Pending further analysis, we also recommend compliance with the International Residential Code (IRC) (2012) requirements for air impermeable insulation in sealed and insulated assembles, as they vary by climate zone and roof finish.

- *When might a builder/designer choose a sealed and insulated attic from amongst the advanced attic/roof options in the energy code?*
    - Complex roof designs make provision of adequate vent area impossible or overly complex.
    - Complex ceiling configurations or numerous penetrations make air sealing at the attic floor undesirable, or complicate construction of dropped ceiling or attic duct chases.
    - HVAC subcontractor is not familiar with providing high performance equipment and distribution systems.
    - They are building in locations currently recognized by the IRC as requiring no air impermeable insulation.

- They want low costs and the highest performance.
- They want to avoid construction of chases and other such oddities to contain ducts within a vented attic.
- They want to avoid specification of complex and unfamiliar assemblies, including phase change materials and vented roof decks.
- They want ducts to remain accessible for inspection, additions and repairs.
- They want the attic to be available for storage space.

Table of Contents

List of Tables

List of Figures

Introduction

The vast majority of new homes built in California have HVAC systems located in traditional vented attics. These vented spaces experience the most extreme thermal conditions of any location in the home, with winter temperatures similar to outside and summer temperatures often over 120°F (48.9°C). This challenging environment exacerbates any energy losses from the HVAC system and its ducts, and can have a disproportionate effect on system performance. As new California homes move towards being zero net-energy by 2020, advanced roof constructions, including sealed and insulated attics, are key strategies to be used in further reducing building loads—bringing renewable generation closer to satisfying all household demand.

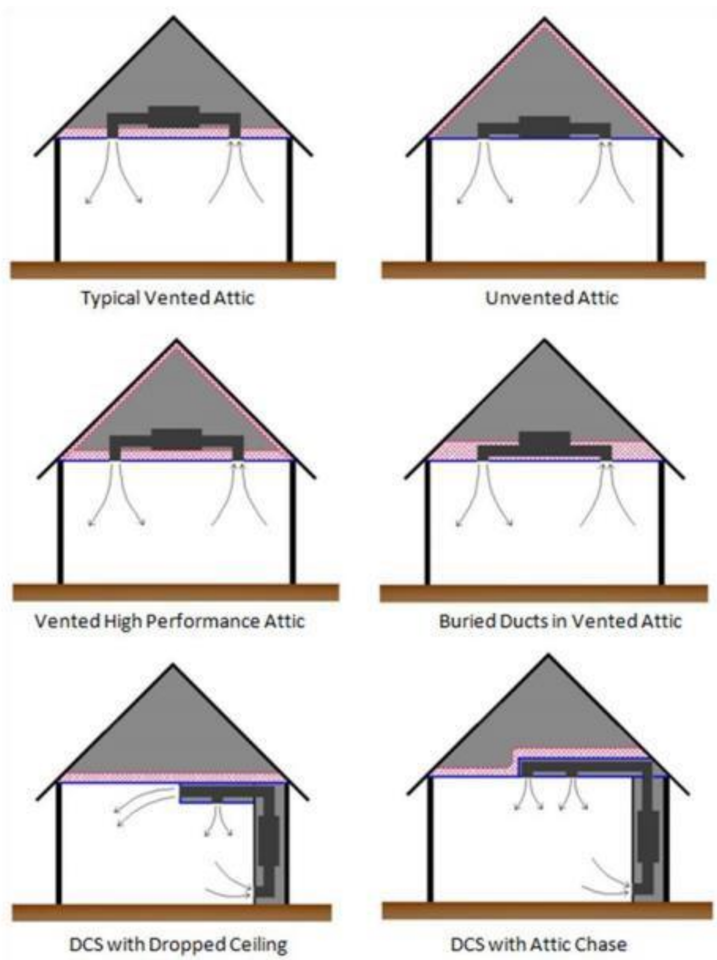

Figure 1 Illustration of advanced roof/attic construction and design options. Source: Hoeschele et al

As is currently proposed for the new reference home[5] in California's 2016 Title 24 Building Energy Code (California Energy Commission, 2015a), 'advanced roofs' will be:

- Vented,
- With R13 below deck in rafters (or R6 above roof deck)[6],
- 5% duct leakage,
- R8 duct insulation,
- Radiant barrier and cool roof requirements, varying by climate zone.

Alternatives to this baseline 'advanced roof' must use the code's performance path, and they include high performance attics that bring ducts inside conditioned space. These strategies can include vented attic designs (e.g., plenum truss systems, built-up duct chases, and dropped ceiling chases), as well as sealed and insulated attics. Traditional vented attics can also comply with the energy code using the performance path. An alternative option is to bury the ducts in insulation. A number of these options are illustrated in Figure 1. Others have provided detailed reviews with cost and energy assessments of these approaches in the context of new California homes (GARD Analytics, Inc., 2003a, 2003b; Hoeschele, Weitzel, German, & Chitwood, 2015; Wei, Pande, Chappell, Christie, & Dawe, 2014). These advanced roof approaches are being pursued in parallel with other efforts to optimize HVAC performance in new California homes, namely through design and construction of compact duct systems, and improvements to insulation and airtightness of ducts. By far, sealed and insulated residential attics have received the greatest degree of study and assessment in the research literature, with documented use and proven performance for at least two decades in high performance homes throughout the U.S.

While select production builders have years of experience with sealed and insulated attics in California[7], most building professionals in the state are unfamiliar with sealed and insulated attic construction. The building trades, namely framing, HVAC and insulation subcontractors are not accustomed to the methods and requirements of sealed and insulated attic construction. Building trades may need to be rescheduled with changes to scopes of work. Design changes include those to architectural, structural and mechanical scopes of work. This approach is not a trivial departure from standard practice. The most common implementation of sealed and insulated attics has been through use of spray polyurethane foam (SPF) insulation, which is much more expensive than fibrous insulation solutions, such as fiberglass and cellulose. Furthermore, accumulation of moisture and building assembly degradation in sealed and insulated attics have been predicted and occasionally reported in the field and in the research literature.

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[5] Component Package A, Options A and B.

[6] This assumes an air space. With no air space, below deck requires R18 and above deck R8.

[7] Hoeschele et al. (2015) suggest that production builder—Meritage homes—has built over 10,000 units using sealed and insulated attics insulated with low-density spray polyurethane foam.

The purpose of this report is to review the available scientific literature related to the construction and performance of sealed and insulated residential attics, as well as other relevant high performance roof/attic systems. The review will cover a variety of topics including attic performance simulation models, building codes, and field experience on the thermal and moisture performance of attics, attic airtightness and energy performance. This review will be used to generate insights and guidance for successful construction and implementation of this strategy in new California homes in ways that will mitigate risk and enhance system performance.

2 Background on Residential Attic Venting

The question of whether or not to vent residential attics has received considerable attention in the building science research literature. Lstiburek (2006, 2014) provide very good introductions to residential attic ventilation (Lstiburek, 2006, 2014). Similarly, Rose & TenWolde (1999) provide an excellent summary of the history and pertinent issues, as they vary with climate zone (TenWolde & Rose, 1999). These authors conclude broadly that while sometimes beneficial, attic ventilation should not be the primary strategy for eliminating moisture, thermal and other problems in roofs/attics. They argue that for every benefit attributed to attic ventilation—reducing moisture problems, eliminating ice dams, ensuring shingle life, and reducing cooling demand—other strategies have been demonstrated to have stronger and more direct influence. In fact, in some cold marine climate zones, attic ventilation has been shown to contribute to, rather than alleviate, moisture problems (Finch, LePage, Ricketts, Higgins, & Dell, 2015; T.W. Forest & Walker, 1993; Newport Partners, LLC, 2004; Walker & Forest, 1995) . While its merits may be debatable, the building codes have unanimously required the provision of venting area in residential attics. That is until recent versions of the model International Residential Code (IRC) and the International Energy Conservation Code (IECC), which have provided specifications for use of sealed and insulated attic/roof assemblies.

Sealed and insulated approaches are becoming more popular in new residential construction, with some estimates that over 100,00 sealed and insulated attic units have been constructed in the U.S. (Schumacher, 2007). This is supported by California market research provided in Wei et al. (2014), who list several large production home builders who have experience with sealed and insulated attics in California and across the U.S. Parker (2005) provides a valuable review of attics literature, with particular emphasis on performance of sealed and insulated attics (Parker, 2005a).

Currently, attics/roofs can be designed to be either vented or sealed and insulated in any climate zone in the United States. The model building codes do not require one approach over another, but the code does stipulate design approaches that limit the risk of moisture damage. Numerous approaches and materials are available to designers, with widely varying costs, ease of implementation and performance.

Potential ***advantages*** attributed to sealed and insulated attic designs include:

- Placement of a home's primary air and thermal boundaries at the sloped roof surface in large part brings the attic (and any HVAC equipment located in the attic) into conditioned space, even when no direct conditioning is provided. This leads to small temperature differences between the attic and the occupied space of the home. Relative to traditional vented attics, sealed and insulated attic air temperatures are generally warmer during winter and cooler during summer.
- HVAC loads are often reduced for systems located in the attic, due to the tight coupling of house and attic air temperatures.
- Remaining thermal losses from the HVAC system, due to air leakage for example, are recaptured in the home's conditioned space. As a result, inefficiencies in the HVAC system (e.g., low refrigerant charge, poor airflow design, duct air leakage) have less effect on whole house performance.
- As a result of improved thermal performance, air conditioner capacity may be reduced by approximately 0.5 refrigeration tons for a typical sized home.
- Reduces peak demand during afternoon summer cooling periods.
- Reduces potential for condensation to occur on HVAC ducts in cooling operation.
- Placing ducts in conditioned space can help to eliminate air pressure differences throughout the home that are induced by HVAC operation.
- Moves primary air and thermal barriers to the roof deck, which permits complex ceiling designs, ceiling height changes and numerous ceiling penetrations from lighting and services.
- Some sealed and insulated attic designs can easily accommodate complex roof plans, which are very difficult to vent properly.
- Eliminates wind-driven snow in cold climates, wind-driven rain penetration in coastal climates, and wind-driven embers from wild fires.
- A sealed and insulated, conditioned attic provides additional living and storage space.

Potential ***disadvantages*** attributed to sealed and insulated attic designs include:

- Increases roof surface area for air leakage and heat loss/gain (combined sloped roof and gable surface area exceeds attic floor area), and increases material costs for insulation.
- Increases temperature difference across the thermal boundary during cooling hours (shingles-to-attic-air vs. attic-air-to-house).
- Sealed and insulated attics that do not achieve sloped roof R-values equivalent to those specified for flat ceilings may offer less thermal resistance and little or no energy benefits, even when insulated with spray polyurethane foam (SPF) insulation.

- It may be substantially more difficult to install insulation at the structural roof sheathing than on the flat ceiling.
- Increases roof shingle and structural sheathing temperatures.
- Any gas appliances located in a sealed and insulated attic must use sealed combustion, because they lack combustion and ventilation air paths to outside.
- Placing insulation at the roof deck can cool the roof sheathing in winter, which might lead to condensation and moisture accumulation in the roof assembly. In summer, roof sheathing and cladding temperatures are expected to increase.
- Sealed and insulated attics may cost more to build than vented attics.
- Exposed and untreated SPF insulation in sealed and insulated attics may violate fire provisions in the building code.

3 Attic Thermal and Hygrothermal Models

In order to develop models and a deeper understanding of attic performance it is necessary to understand the physics of mass and energy transport in attics. Residential attics containing forced air heating and cooling equipment are an incredibly complex hygrothermal environment. Heat and moisture are exchanged between the house, the attic, the HVAC system, construction materials and outside. Transport mechanisms for heat and moisture vary dramatically by time of day and season. Roof materials are exposed to the most extreme temperature and radiation conditions of any assembly in the home. Heat transfer by radiation, conduction and convection are all crucially important to the performance of a residential attic. Moisture transport occurs through mass flow, diffusion and condensation. Many of these mechanisms vary diurnally and seasonally, with wide swings of wetting and drying periods. To illustrate the complexity of heat, moisture and mass transport in residential attics, simplified representations of attic heat transfer, attic and house mass flow paths and radiation heat transfer paths are provided in Figure 2, Figure 3 and Figure 4, respectively.

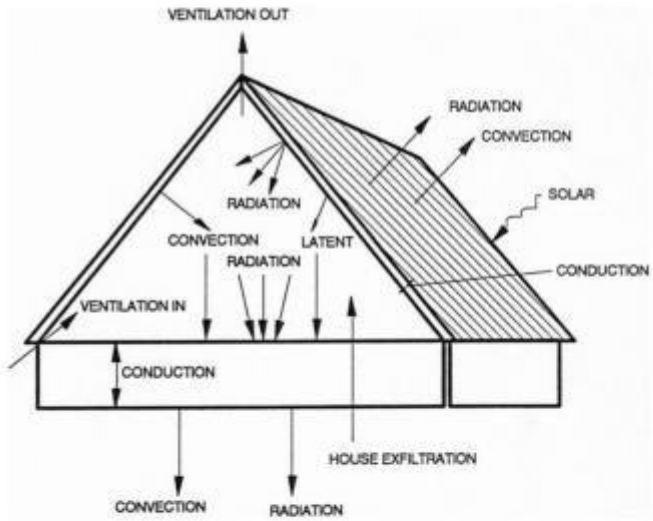

Figure 1 *Schematic of a typical attic showing the various heat transfer mechanisms that occur within it.*

Figure 2 Figure 2 Illustration of heat transfer flow paths in a vented attic. Source: DesJarlais et al. (2004).

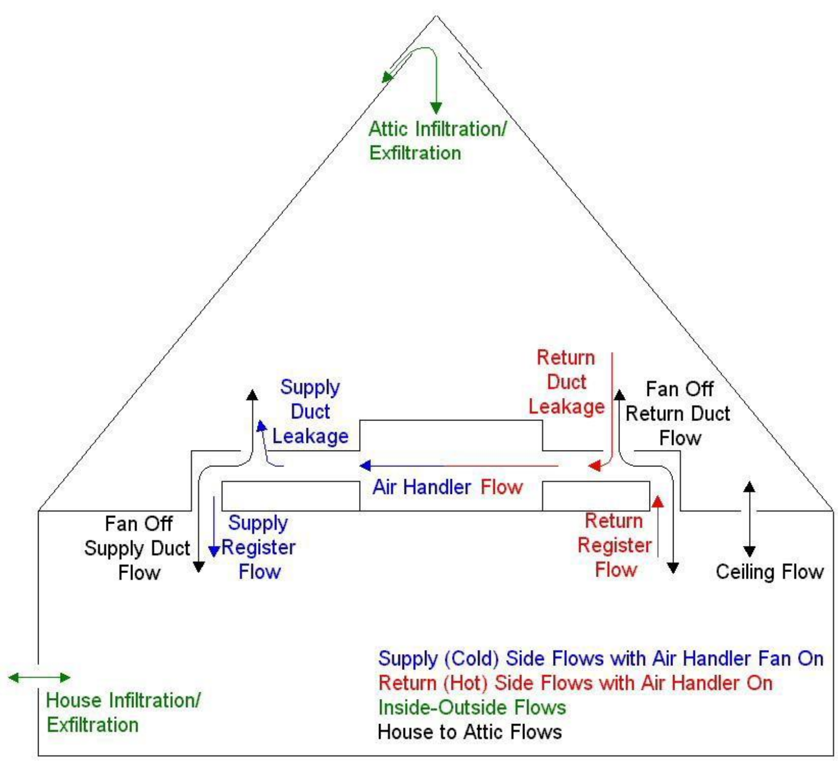

Figure 3 Schematic representation of air and mass flow paths in residences. Source: Lstiburek et al. (2007).

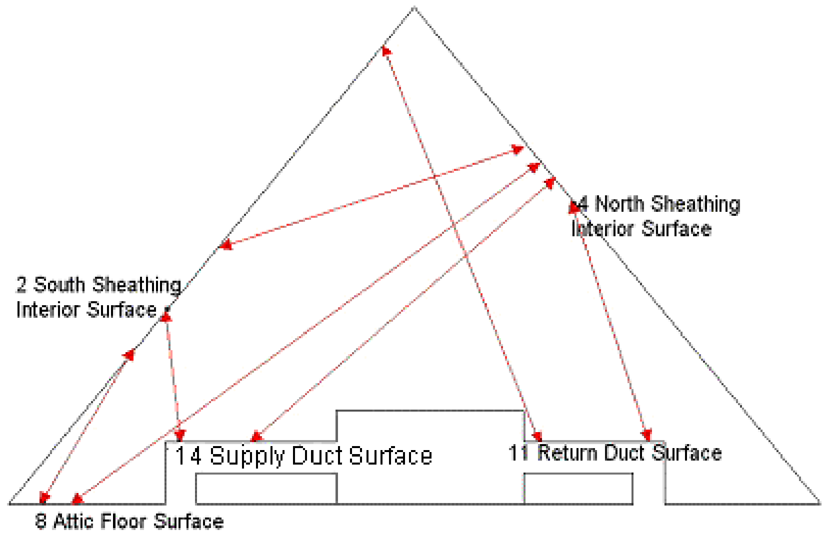

Figure 4 Schematic representation of radiant heat transfer in residential attic. Source: Lstiburek et al. (2007).

Prediction of the attic ventilation and thermal or hygrothermal performance has developed over-time. Early tools dealt almost exclusively with the prototypical sloped roof, vented attic construction. Parker (2005) provides an excellent summary of the historical development of some of the primary attic simulation approaches (Parker, 2005b). Walker (1993) treats some of the early models in much greater detail, comparing them against the transient heat, mass and moisture model developed in his work (Walker, 1993). A number of attic thermal models exist in the literature (Abrantes, 1985; Peavy, 1979; Wilkes, 1989), as well as attic moisture models (Burch & Luna, 1980; Cleary, 1985; Ford, 1982; Gorman, 1987). These moisture models all include thermal models, because mass transfer processes in wood are strong functions of temperature. These past moisture models were limited, because of their simplified treatment of: (1) attic ventilation and ceiling airflow, (2) wood moisture content, surface condensation and mass balances, and (3) use of primarily steady-state solutions, ignoring transient effects.

Current tools are used to predict the performance of more complex assemblies, including sealed and insulated attics, cool roof surfaces and advanced roofing strategies, such as incorporation of phase change materials and roof deck venting. These more complex approaches often necessitate the use of several independent tools either in-series or iteratively. Unfortunately, many of the current tools suffer from some, but not all, of the limitations of past models listed above.

Tools that are currently used in assessments of residential attics fall under several broad types: (1) assembly-based tools, (2) full attic models and (3) house-attic system models.

3.1 Assembly-Based Tools

One- or two-dimensional construction assembly-based tools are used primarily to predict the time varying moisture contents of construction materials as they are exposed to time varying indoor and outdoor conditions, including rain intrusion. Assembly moisture content and humidity are then compared against established criteria, such as those in ASHRAE Standard 160 (ASHRAE, 2009). Outside conditions are determined from weather files (typically TMY2 or TMY3), and interior conditions are derived from external sources, such as assumed design conditions (such as those in ASHRAE 160) or predictions from a building simulation model. Examples of these types of tools include WUFI and THERM (Fraunhofer IBP, 2015; LBNL, 2013). The strengths of these tools are their ability to vary the parameters of the assembly in detail, such as insulation conductance, permeance, moisture storage, inclusion of vapor barrier or retarders, etc. The drawback is that they are not attached to a credible thermal and moisture model of the attic space or house below (and its systems). So, this information must be determined through other simulation efforts (e.g., EGUSA, BEopt, etc.), relationships with outdoor conditions (e.g., EuroNorm), or assumed conditions (e.g., design-day conditions or "worst-case").

3.2 Full Attic Models

Full attic models typically are focused on predicting non-assembly based performance of attics, such as air exchange with outside and with the house, attic thermal and moisture properties, prediction of heat flux and potentially interactions with HVAC forced air distribution systems. Examples of these types of attic models include the ASTM Standard C1340/C1340M-10, AtticSim, AtticSim II (ORNL), Fraunhofer Attic Thermal Model (FATM), ATTIX (CMHC) and the Forest Products Laboratory Roof Temperature and Moisture Model. As with the assembly-based tools described above, full attic models still lack the ability to determine the conditions of the house volume, and therefore the thermal and moisture interaction between the two spaces is ignored or developed elsewhere.

3.3 House-Attic System Models

Models of entire house-attic systems provide integrated assessments of structures as combined systems. Examples of this type of simulation include the REGCAP model, FSEC 3.0 and WUFI Plus, all of which contain thermal, moisture and mass transport assessments of house, HVAC and attic zones with varying levels of detail and sophistication. These types of models provide all information necessary to fully predict performance of residential attics, as they interact with house and exterior conditions. This excludes detailed transient performance of the assemblies themselves, as is dealt with in assembly-based tools.

3.4 Limitations and Use in the Literature

While there are many models that ostensibly claim to do the same thing—predict attic performance—they differ in a number of important ways. These include their: (1) suitability for use with sealed and insulated attics, (2) accounting for HVAC operation and distribution system interactions, (3) models of air exchange with house and outside and (4) dealing with stratification within the attic volume. Infiltration and ventilation models for coupled house-attic systems are very often simplified in the models reviewed here. For example, the attic air exchange rate with the house and outside are often simply inputs by the users, rather than values determined through simulation. The FPL model described by TenWolde (1997) has user-specified attic air exchange. Similarly, ASTM C1340 (AtticSim) assumes a constant thermal condition in the house below, and includes a one-direction exfiltration of air from the house to the attic; it is not specified how the magnitude of this exfiltration is determined. The attic ventilation model in ASTM C1340 also appears to assume a direction of attic airflow, from the eaves to the ridge. A similar assumption is made in the FSEC 3.0 attic model. Many of the models were developed in the context of vented, unconditioned attics, and have not been validated using data from modern sealed and insulated assemblies. Some simulations used in the literature do not adequately describe radiation exchanges occurring in attics, namely those for predicting whole house energy performance using DOE2.1.

The addition of simulation model features that represent next generation attic and roof designs are also problematic, though necessary for advancing roof and attic performance. For example, the addition of a ventilation channel between the structural roof sheathing and the roof finish materials may have substantial energy and moisture benefits. This insight has been supported by field measurements (W. A. Miller, 2006). These researchers have also proposed a mathematical model for estimating airflow and heat/mass transfer in such ventilated roof decks (W. A. Miller, Keyhani, Stovall, & Youngquist, 2007). A review of this model suggests that it accounts only for buoyancy driven airflows in the ventilation gap, an approach that completely ignores the potentially dominant wind-driven airflows. Furthermore, the model is not appropriate for predicting performance of vented roof decks, with ventilation channels running horizontally, as opposed to vertically. The horizontal approach is the default method used when installing tile roof finishes over wood battens. A double batten approach is proposed, but represents a substantial departure from common practice.

As noted above, it was common in the reviewed literature that multiple tools were needed to perform useful assessments of attic thermal and moisture performance. For example, Prahl & Shaffer (2014) combined visual assessments of sealed and insulated attics, 3-d geometric modeling at air leakage paths, computational fluid dynamics to determine leak characteristics, house and attic airflow modeling with CONTAM, BEopt modeling of house temperature and humidity conditions and finally WUFI to assess moisture dynamics in the construction assemblies due to air leakage in the sealed and insulated attic. Needless to say, compounding errors and misaligned assumptions of the varying tools could derail these types of assessments in series. Pallin, Kehrer & Miller (2013) developed a model of coupled house, HVAC system and sealed and insulated attic thermal and moisture performance using MATLAB, along with simulation of sealed and insulated attic assemblies using two WUFI 1-D models—one for each primary roof plane (Pallin, Kehrer, & Miller, 2013).

Salonvaara, Karagiozis & Desjarlais (2013) used a combination of WUFI Pro and WUFI Plus for whole building simulation.

4 Sealed and Insulated Attics and the Building Code

4.1 2013 California Building Standards Code, Title 24, California Code of Regulations

The 2013 California Residential Code (Title 24, Part 2.5 of the California Building Standards Code) (California Building Standards Commission, 2013) has provisions for minimum attic vent area, as well as requirements for sealed and insulated attic construction. The California Energy Code (Title 24, Part 6) provides energy-related requirements for all residences (California Energy Commission, 2015a).

4.1.1 Attic Vent Area Requirements

The 2013 California Residential Code (Chapter 8, *Roof-Ceiling Construction,* Section R806.2) requires that vented attics have net-free attic vent area of at least 1/150 of the area of the vented space. Exceptions allow vent area to be as low as 1/300 of the area of the vented space, under the following conditions:

- In CEC Climate Zones 14 and 16, a Class I or Class II vapor retarder is installed on the warm-in-winter side of the ceiling.
- 40-50% of the required vent area must be located in the upper portion of the attic, no more than 3' below the highest point in the attic. The balance of the vent area should be provided by either eave or cornice vents.

4.1.2 Sealed and Insulated Attic Requirements

The 2013 California Residential Code (Chapter 8, *Roof-Ceiling Construction,* Section R806.5) describes the following requirements for sealed and insulated attic and sealed and insulated enclosed rafter assemblies[8]:

- Sealed and insulated attic space is to be completely contained with the building's thermal boundary.
- No interior Class 1 vapor retarders are installed on the ceiling side of the assembly.
- Use of wood shingles or shakes requires ¼" air space between shingles and roof underlayment.
- In CEC Climate Zones 14 and 16 any air impermeable insulation shall be a Class II vapor retarder, or have a Class III vapor retarding coating or covering in direct contact with the underside of the insulation.

[8] These requirements are based on the 2012 International Residential Code, whose sealed and insulated attic requirements are summarized in Section 4.2.

- Depending on the permeability of the insulation used in the sealed and insulated attic assembly, one of the following must be met[9]:
    - Air impermeable insulation only, applied in direct contact with underside of structural sheathing.
    - Air permeable insulation only in the cavity, with continuous exterior insulation of at least R-4.
    - When a mix of air permeable and impermeable insulation is used in the cavity, the air impermeable insulation shall be installed in direct contact with the underside of the roof sheathing[10].

4.1.3 Title 24 Part 6, Energy Code Requirements

The Title 24 Building Energy Code includes mandatory requirements, as well as prescriptive and performance paths to compliance. Items relevant to sealed and insulated attics are described below.

4.1.3.1 Mandatory Requirements

The most directly relevant envelope mandatory requirement is that wood-framed roof/ceiling construction assemblies must have at least R-22 insulation, or a maximum U-factor of 0.043 based on 16 inch on center wood-framed rafter roofs. This forms the minimum installed insulation value for sealed and insulated attics pursuing the code's performance path to compliance. Other mandatory envelope features include radiant barrier and cool roof requirements, but these simply require that products be rated and labeled, or they define acceptable performance criteria, such as emittance of a radiant barrier.

For HVAC systems, heating and cooling equipment minimum efficiencies are specified, and system size must be calculated using ACCA Manual J or equivalent methods. Duct sealing and insulation are required in all locations. For ducts inside conditioned space, a minimum of R-4.2 is required. Ducts must be confirmed as inside conditioned space by visual inspection and testing of leakage to outside (See Reference Appendix RA 3.1.4.3.8) by a HERS rater. In all other cases the minimum duct insulation is R-6. All ducts must be measured for air leakage and have no more than 5% leakage, where the total system air flow is based on the nominal heating and cooling equipment capacity. HVAC distribution fans must provide at least 350 CFM per ton of nominal capacity, and they must do this using less than 0.58 watts per CFM. Minimum MERV 6 filtration is required in all air-handling units. All homes are also required to meet the provisions of ASHRAE Standard 62.2-2010 (plus

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[9] Sealed and insulated attics can be constructed under the California Residential Code without any insulation installed on the underside of the roof sheathing, if the attic floor is insulated, the roof finish is vented (i.e., tiles or wood shakes on battens) and no continuous underlayment is installed with perm rating no more than one perm (dry cup method).

[10] This provision is unclear, because it does not state how much air impermeable insulation is required.

several addenda), which specifies requirements for mechanical ventilation and other related measures.

4.1.3.2 Prescriptive Compliance Paths

The 2016 version of the California Title 24 Building Energy Code includes numerous provisions for high performance attics and roof systems, and the code offers flexibility to designers/builders in achieving energy performance goals. Any sealed and insulated attics must comply using the code's performance path requirements, and their energy performance must be equivalent to the prescriptive paths described below.

For ***vented attics***, three approaches are available for prescriptive compliance:

- *High Performance Ventilated Attic (HPVA) Option A*, requires continuous insulation to the exterior of the roof sheathing, as well as insulation on the flat ceiling.
- *HPVA Option B* requires insulation installed below the roof sheathing, as well as on the flat ceiling.
- *Ducts in Conditioned Space (DCS) Option C* requires that the air handler and ducts be located inside the conditioned volume of the home, with field verification required for prescriptive compliance, namely duct leakage to outside shall be measured to be less than 25 cfm (form CF2R-MCH-20b).

A flow chart describing these three options is reproduced from the Title 24 codes in Figure 5, and a simple checklist is reproduced in Table 1. In the Title 24 2016 Residential Compliance Manual Chapter 3 (*Building Envelope Requirements, Section 3.6.2.1*), compliance options and best practices are detailed for meeting the High Performance Vented Attic (HPVA) requirements. Duct placement and HVAC requirements for HPVA are detailed in Chapter 4 (*Building HVAC Requirements, Section 4.4.2.1*). Specific requirements for each of these options depend on whether or not the roof cladding has a vent space behind it, as is typical with tile roof materials. Insulation and cool roof requirements for each California climate zone are provided for these options in Table 2. Wei et al (2014) outline development of these packages and provide detailed energy savings estimates.

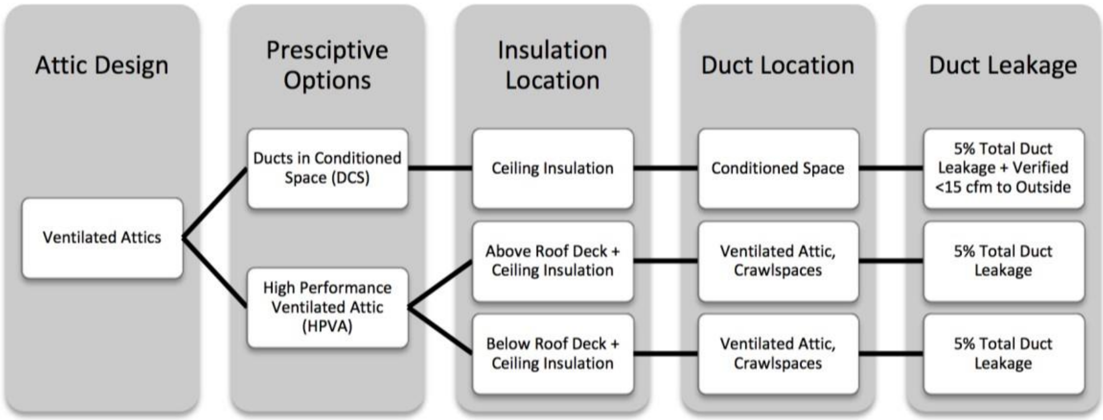

Figure 5 Title 24 2016 Ventilated attic prescriptive compliance choices. Source: Figure 3-15 in Section

Option A (CZ 4, 8-16)	Option B[1] (CZ 4, 8-16)	Option C (CZ 4, 8-16)
☐ Vented attic ☐ R6 (air space) or R8 (no air space) continuous above deck rigid foam board insulation ☐ R38 ceiling insulation ☐ Radiant Barrier ☐ R8 duct insulation ☐ 5% total duct leakage	☐ Vented attic ☐ R13 (air space) or R15 (no air space) batt, spray in cellulose/fiberglass below roof deck secured with netting, or SPF ☐ R38 ceiling insulation ☐ R8 duct insulation ☐ 5% total duct leakage	☐ Vented attic ☐ R30 or R38 ceiling insulation (climate zone specific) ☐ R6 or R8 ducts (climate zone specific) ☐ Radiant Barrier ☐ Verified ducts in conditioned space
[1] Standard Design used to set the energy budget for the Performance Approach.		

Table 1 Title 24 2016 checklist for prescriptive requirements for HPVA/DCS for the related climate zones. ***Source: Figure 3-17 in Section 3.6.2.1 of Title 24.***

Attic/Roof Option	*Element or Criteria*	*CEC Climate Zones*															
		1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
A	*Air Gap, NO – Insulation (R)*	NR	NR	NR	8	NR	NR	NR	8	8	8	8	8	8	8	8	8
	Air Gap, YES – Insulation (R)	NR	NR	NR	6	NR	NR	NR	6	6	6	6	6	6	6	6	6
	Ceiling Insulation (R)	38	38	30	38	30	30	30	38	38	38	38	38	38	38	38	38
	Radiant Barrier (Y/N)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
	Duct Insulation (R)[11]	8	8	6	8	6	6	6	8	8	8	8	8	8	8	8	8
B	*Air Gap, NO – Insulation (R)*	NR	NR	NR	15 [12]	NR	NR	NR	15	15	15	15	15	15	15	15	15
	Air Gap, YES – Insulation (R)	NR	NR	NR	13	NR	NR	NR	13	13	13	13	13	13	13	13	13
	Ceiling Insulation (R)	38	38	30	38	30	30	30	38	38	38	38	38	38	38	38	38
	Radiant Barrier (Y/N)	N	Y	Y	N	Y	Y	Y	N	N	N	N	N	N	N	N	N
	Duct Insulation (R)	8	8	6	8	6	6	6	8	8	8	8	8	8	8	8	8
C	*Ceiling Insulation (R)*	38	30	30	30	30	30	30	30	30	30	38	38	38	38	38	38
	Radiant Barrier (Y/N)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
	Duct Insulation (R)	6	6	6	6	6	6	6	6	6	6	8	6	6	6	6	6
Low-Slope	*Aged Solar Reflectance*	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.63	NR	0.63	NR
	Thermal Emittance	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.75	NR	0.75	NR
Steep-Slope	*Aged Solar Reflectance*	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.2	0.2	0.2	0.2	0.2	0.2	NR
	Thermal Emittance	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.75	0.75	0.75	0.75	0.75	0.75	NR

Table 2 Reproduction of Roof/Attic requirements from Appendix B Table 150.1-A for prescriptive compliance with the Title 24 2016 Building Energy Code.

4.1.3.3 Sealed and Insulated Attics and the Performance Path to Compliance

Notably, the CEC estimates that 95% of permit applications for new home construction use the performance path for compliance, which is described in Chapter 8 of the 2016 Residential Compliance Manual (California Energy Commission, 2015b). The performance path requires that the time-dependent valuation (TDV) energy use of the proposed design be equal to or less than that for a similar home (i.e., same floor area, volume and surface area) meeting the Prescriptive Package A Option B, whose roof/attic requirements were detailed above in Section 4.1.3.2.

Performance path projects must still meet the Mandatory elements of the Title 24 code. For example, an sealed and insulated attic using the performance method

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[11] Ducts in conditioned space can have a minimum R-value of 4.2, which is only allowed when using the performance path to compliance.

[12] Notably, in Table 150.1-A, rafter insulation requirements for roofs without vented cladding are labeled as R-18. This contradicts what is written in other locations, such as in Table 1. We believe the R-15 value is correct; it is also consistent with the R-6 vs. R-8 specification for Option A compliance (i.e., no vent space gives +R-2).

would still need to follow the mandatory requirement of sealed and insulated HVAC ducts, with maximum tested air leakage of 5% of nominal system airflow and a minimum of R-4.2 insulation (even in conditioned space). Performance path homes must also meet any pertinent provisions in the California Residential Code described in Section 4.1.1 and 4.1.2 above.

4.2 Model Building Code Provisions

4.2.1 Air Impermeable Insulation Requirements

The model 2009 and 2012 International Residential Codes (IRC) contain requirements for sealed and insulated attics and sealed and insulated enclosed rafter assemblies in section R806.5 (ICC, 2012b). The follow are required for permitting:

1. Sealed and insulated attic space must be completely contained within the building thermal envelope.
2. No interior Class 1 vapor retarders are allowed on the ceiling side (attic floor) of the sealed and insulated attic or on the ceiling side of the sealed and insulated enclosed rafter assembly.
3. Where wood shingles or shakes are used, a minimum of ¼” vented air space is required to separate the shingles from the roof underlayment.
4. In climate zones 5-8 any air impermeable insulation shall be Class II vapor retarder, or shall have a Class II vapor retarder coating or covering in direct contact with the underside of the insulation.
5. Meet one of the following conditions, depending on the air permeability of the insulation in direct contact with the structural sheathing:
    a. Air impermeable insulation only, insulation shall be applied in direct contact with the underside of the roof sheathing.
    b. Air permeable insulation in the rafters, combined with air impermeable insulation, either against the underside or topside of the structural roof sheathing as per Table 806.5.
    c. Where pre-formed insulation board is used as the air impermeable layer, it shall be sealed at the perimeter of each sheet to form a continuous layer.

Table 3 (IRC 2012 Table 806.5) contains code requirements for sealed and insulated attics. Namely, when air permeable insulation is installed in the rafters, then a layer of air impermeable insulation is required. The air impermeable insulation must be installed in direct contact with the roof sheathing. IECC 2012 (ICC, 2012a) climate zones that are located within California include 2B, 3B, 3C, 4B, 4C, 5B, 5C and 6B. This air impermeable insulation layer is intended to increase the temperature of the first condensing surface, to alleviate risk of condensation and moisture accumulation in sealed and insulated attics using air permeable insulation.

Climate Zone	*Minimum Air Impermeable Insulation R-Value*	*2012 IECC Required Total R-Value*
2B and 3B tile roof only	0	30
1, 2A, 2B, 3A-C	5	38
4C	10	38
4A-B	15	49
5	20	49
6	25	49
7	30	49
8	35	49

Table 3 2012 International Residential Code, Sealed and insulated Attics Table 806.5.

4.2.2 Ignition Barrier Requirements

The ICC Section R316.4 stipulates that SPF must be separated from the living space by an "approved thermal barrier" (default is 0.5" gypsum board). In the current market, many SPF manufactures have had their products tested and certified to act as thermal barriers without further protection. In many past installations, additional ignition barriers were required, most commonly intumescent coatings. In its ICC-ES Evaluation Reports for SPF manufacturers that intumescent coatings can be used on exposed SPF foam in attics and in crawlspaces when: (1) attic entry is for service of utilities only, no storage is allowed, (2) the attics is not interconnected with the crawlspace or basement, (3) air in the attic is not circulated to other parts of the buildings and (4) combustion air is provided. In practice, this has meant that intumescent coatings are applied to the interior surface of SPF foam exposed in most sealed and insulated attics. But in cases where the attic is actively conditioned with HVAC supply and exhaust air[13], a prescriptive thermal barrier (e.g., 0.5" sheetrock) is required. Alternatively, the International Mechanical Code specifies requirements for smoke detectors in commercial building forced air systems, where a triggering of the alarm shuts off fan operation. This approach is used in some sealed and insulated attic homes (Bailes, 2014; Lstiburek, 2014), but it is not currently recognized in the Model Codes.

5 Cost of Sealed and Insulated Attics

The cost of sealed and insulated attic construction has not been widely reported in research or trade literatures, though what is available suggests that the price increase for new homes is on the order of \$700 to \$3,000, averaging roughly \$1,000 per home (from \$0.60 to \$1.40 per ft^2 of attic floor area (\$6.46 to \$15.07 per m^2). This varies with the size of the home, number of stories, insulation materials used, and the ability to absorb or distribute one-time information/design costs. These

[13] This practice has become increasingly common, and is now recommended by a number of respected experts in this field (Lstiburek, 2014; W. A. Miller, Desjarlais, & LaFrance, 2013).

costs are roughly equivalent with other options for placing ducts in conditioned space.

Hoeschele et al. (2015) provide the most recent reporting of costs for sealed and insulated attics in new California homes. They report estimates from production builder, Meritage Homes, who has constructed over 10,000 sealed and insulated attic units in California using open cell SPF. So, unlike other estimates reported in the literature, these can be considered "mature" market costs (though costs to this production builder may not reflect typical market rate costs for SPF). Meritage cost estimates are adjusted by the authors for the cost of HERS duct airtightness testing and for an increase from their standard R-20 specification to an R-30 spec. Credits are assumed for a smaller HVAC system and the like. The one-story 2,100 ft^2 (195 m^2) prototype home cost an estimate of $2,885 ($1.37 per ft^2 ($14.75 per m^2)), and the two-story 2,700 ft^2 (251 m^2) prototype was $1,864 ($0.69 per ft^2, $1.38 per ft^2 of attic floor area ($7.43 per m^2, $14.85 per m^2 of attic floor area)). Notably, these costs assume use of ocSPF, which is substantially more expensive than the fibrous insulation solutions being explored in this CEC research. The authors also provide cost estimates for approaches to ducts in conditioned space Option C from the 2016 Title 24 energy codes. Attic chases are estimated to cost $2,388 to $3,129 depending on floor area, and dropped ceiling approaches cost between $638 and $811. They estimate substantial reductions in costs for these methods if compact, high performance duct designs are implemented in the future.

Other reports of sealed and insulated attic costs are somewhat dated, but still worth reporting. GARD Analytics Inc. (2003) reported costs of sealed and insulated attic construction to the builder, using standard cost estimating guides, component costs with subs and suppliers, cost estimates from production builders, and cost estimates from a builder using the sealed and insulated attic approach (GARD Analytics, Inc., 2003a). Cost estimates for the sealed and insulated attic ranged from a savings of $800 to a cost increase of around $1,500, when jump ducts and outdoor air ventilation are included. The cost savings came from an assumption of a reduced size, compact duct system. With standard duct systems, costs estimates are between $773 and $1,335. An average of actual builder estimates for sealed and insulated attics was $1,038 per home ($0.78 per ft^2 attic floor area ($8.40 per m^2)). The authors reported their combined best estimate for sealed and insulated attics of $700 (0.5% of total construction cost) for 1-story and $0 (0%) for 2-story single-family homes. These best estimates assume an R-30 roof deck. An R-39 requirement would increase costs by around $100. If savings for a compact duct system were not included, then costs would increase $500 and $2000 for 1- and 2-story homes. Similarly, Parker (2005) reported that sealed and insulated roof construction typically increased construction costs by approximately $1.00 - $1.50 per ft^2 of floor area ($10.76 to $16.15 per m^2), though the source of this estimate is not clear.

While not necessarily relevant to new construction, Neuhauser (2012) reported on the retrofit costs of four sealed and insulated roofs in a Chicago low-income weatherization pilot program, and the average total cost was $11,087 (from $10,130 to $14,035) (Neuhauser, 2012). Discussions with practitioners have roughly corroborated these retrofit cost estimates.

6 Attic Airtightness and Ventilation

The entire premise of a sealed and insulated attic is that its air exchange with outside is minimized. Sealed and insulated attic designs include those that are directly conditioned by the HVAC equipment, and more commonly those that are incidentally coupled to the house though inadvertent air leakage pathways and thermal coupling. These semi-conditioned sealed and insulated attics act as a buffer zone between the conditioned space and outside. So, all sealed and insulated attics seek to minimize air leakage to outside, and they seek unspecified and varying levels of air exchange with the house. Leakage to outside in sealed and insulated attics may have effects that vary with climate zone. For example, leaks in a sealed and insulated attic might introduce more moisture in hot-humid climates, whereas leaks in hot-dry climate sealed and insulated attics may remove moisture.

We can draw the following conclusions about attic air tightness from the literature:

- Attic airtightness criteria are not included in either the 2012 IRC, or in the U.S. Department of Energy (DOE) Building America Measure Guideline for Sealed and insulated Attic Insulation. We are unaware of any other programs that specify attic airtightness requirements.
- Airtightness tests should be performed in sealed and insulated attic homes, with the attic access(es) fully open. The combined house and attic volumes should meet whatever performance requirement is desired (e.g., 3 air changes per hour at -50 Pascal (ACH_{50}), <0.25 cubic feet per minute of airflow at -50 Pascal per square foot of building envelope surface area (cfm_{50}/ft^2SA)).
- Most sealed and insulated attics remain at least somewhat leaky to both the house and to outside; on average 52% of whole-house leakage area was located in the sealed and insulated attic surfaces (compare to 51% through the ceiling in conventional California (CA) attics).
- Sealed and insulated attics in modern, new California homes (compliant with 2013 Title 24 requirements) may be substantially more airtight than older homes described in earlier research, with median attic air leakage to outside of 246 cfm_{50} (newer homes) vs. 921 cfm_{50} (older homes).
- Sealed and insulated attics are generally somewhat leakier than the houses to which they are attached, but attics are still more coupled to the house than to outside, in terms of heat and mass transfer.
- Sealed and insulated attics insulated with fibrous insulation can achieve airtightness levels comparable to those in attics insulated with SPF.
- Detailed measurements in a single housing development of modern new California homes suggest that duct systems in sealed and insulated attics

have very low air leakage to outside (averaging 1% of total system airflow, or 18 cfm), but substantial leakage still occurs within the envelope (median of 8%, 106 cfm). HVAC systems documented in older research were located inside leakier attics, and as a result, 55% of total duct leakage was to outside (32 cfm to outside on average).

- The airtightness of any duct system located in a sealed and insulated attic should be tested. For the purposes of energy calculations, leakage-to-outside tests should be used, which ignore duct leakage that occurs within conditioned space.
- Common locations for air barrier defects in sealed and insulated attics include (1) plumbing penetrations, (2) framing intersections, (3) roof and wall intersections, and (4) vent locations in existing homes. Common defects include foam delamination, as well as non-existent or inconsistent application of sealants (e.g., caulk, SPF or gaskets).

6.1 Measurement Methods

Measurements of attic airtightness are rare, in either vented or sealed and insulated attics. In the research context, measurements of attic airtightness include use of zonal pressure diagnostics (Center for Energy and Environment, 2001), as well as guarded blower door air leakage tests (Hult, Dickerhoff, & Price, 2012; Sheltair Scientific Ltd., 1989). Zonal pressure diagnostics are the only commonly used method to assess house and attic airtightness by most practitioners in the field. For example, a new tool for ZPD assessments suitable for energy auditors and inspectors was recently released by the company Residential Energy Dynamics (Residential Energy Dynamics, 2015).

Attic air leakage occurs between the house, attic and outside via three primary paths: (1) leakage to outside through intentional vent openings, (2) leakage to outside through unintentional gaps and cracks and (3) interface leakage to the house.

Attic airtightness tests reported in the literature include:

1. Basic zonal pressure diagnostic tests in which house-to-attic pressure is measured, while depressurizing only the house to minus 50 Pa. This pressure will vary between 0 and 50 Pa, reflecting the ratio of leakage areas in the two zones. This test does not indicate the size of the leaks, but rather the relative size of the leaks in the house-attic and attic-outside interfaces. A house-to-attic pressure of zero Pascal means the house and attic are perfectly connected into one volume, while a value of 50pa means the attic and outside are perfectly coupled with respect to the house. A value of 25pa would mean that the attic-to-outside and house-to-attic leakage areas are the same.

2. Single blower door tests of whole house leakage, with the attic access hatch open and closed, which is a version of the “Flow Method” of zonal pressure diagnostics.
3. Multiple blower door “guarded” tests, in which blower doors are placed in the standard door and in the attic access hatch, which allows the user to isolate leakage between the house and attic. These tests partition leakage areas into house-to-outside, house-to-attic (interface leakage) and attic-to-outside.

6.2 Measured Airtightness of Vented Attics

Test methods were developed by the Canadian Mortgage and Housing Corporation (CMHC) in the 1990s to test attic airtightness using pressurized fan methods (Sheltair Scientific Ltd., 1989). Results from three vented attic homes used in test protocol development suggest that ceiling interface leakage is highly variable, from 76 to 2,884 cm^2 (from 4 to 63% of total house leakage area). Attic venting varied from slightly less leakage area than the house to 3.5 times the leakage area. In another Canadian study, 20 attics were tested for airtightness, and house-attic interface leakage area averaged 330 cm^2 (varied from 200 to 450 cm^2), which accounted for an average 38% of total house leakage area (from 4 to 63%) (Buchan, Lawton, Parent Ltd., 1991; Fugler, 1999). Measurements in 31 new California homes suggests that leakage area between the house and attic accounts for 51% of total house leakage area in traditional vented attic homes (Proctor, Chitwood, & Wilcox, 2011). This is comparable to the average 38% found in Canadian research.

6.3 Measured Ventilation Rates in Vented Attics

As reported in the literature, measured ventilation rates for vented attics are highly variable, depending on wind speed and direction, temperature and ventilation opening areas. As a rule of thumb, ventilation rates in conventional vented attics are roughly an order of magnitude greater than those measured inside homes. Wind speed effects dominate attic ventilation rates, whereas attic ventilation rates are weakly dependent on temperature induced stack ventilation (Walker & Forest, 1995). A Summary of some example studies is provided in Table 4. Notably the measurement periods for research in Table 4 are widely variable, from something like one day up to one year. In general, the substantial variability over-time limits the value of any short-term testing. The first five studies listed are reproduced as summarized by Parker (2005b).

Research Report	House Description(s)	Ventilation Rate(s)
Grot and Siu (1979)	3 houses in Houston Texas with soffit vents	1.7 to 2.3 ACH during August
Cleary and Sondregger (1984)	1 house Oroville, CA	4.6 ACH at 7 m/s wind
Ford (1979)	Princeton, NJ	3-4 ACH moderate wind conditions
Dietz et al (1986)	Illinois home	2.9 ACH, long term
Ober (1990)	Two attics in Ocala, FL	0.9 to 1.8 ACH
Walker and Forrest (1995)	2 test attics in Canada	0-6 ACH for relatively tight attic; 0-15 ACH in highly vented attic
(Buchan, Lawton, Parent Ltd., 1991)	20 Canadian residences, including 5 coastal	Varied from 1.1 to 33 ACH; 60% of tests 1-7.5 ACH, 30% from 10-15 ACH, and 10% 15-33 ACH
Miller et al. (2013)	3 test attics in South Carolina	Measured ACH varied from 2 to 3.7 (30 min average)

Table 4 Summary of air exchange rate measurements in vented attics.

6.4 Measured Airtightness of Sealed and Insulated Attics

Measurements of sealed and insulated attic airtightness have included all the methods described briefly above. We assembled all reported airtightness tests for sealed and insulated attics in the literature reviewed in this report, for a total of 75 new and retrofit homes. Summary statistics across metrics of interest are presented in Table 5, and key distributions are pictured in Figure 6. As is common in airtightness testing, researchers did not report consistent metrics, making cross-comparisons and summaries difficult. The vast majority of reported tests were provided in Rudd (2005) and by Hoeschele et al. (2015), in which measurements of 63 homes in California and Arizona are reported (Hoeschele et al., 2015; Rudd, 2005). The Hoeschele et al. (2015) results represent the only data obtained for modern, new homes built to California's Title 24. All subsequent literature added a total of only 12 additional homes, with homes located in cold (Prahl & Shaffer, 2014), mixed-humid (Boudreaux, Pallin, & Jackson, 2013; Salonvaara, Karagiozis, & Desjarlais, 2013), hot-humid (Ueno & Lstiburek, 2015) and hot-dry climates (Rudd & Lstiburek, 1996; Sherman & Walker, 2002).

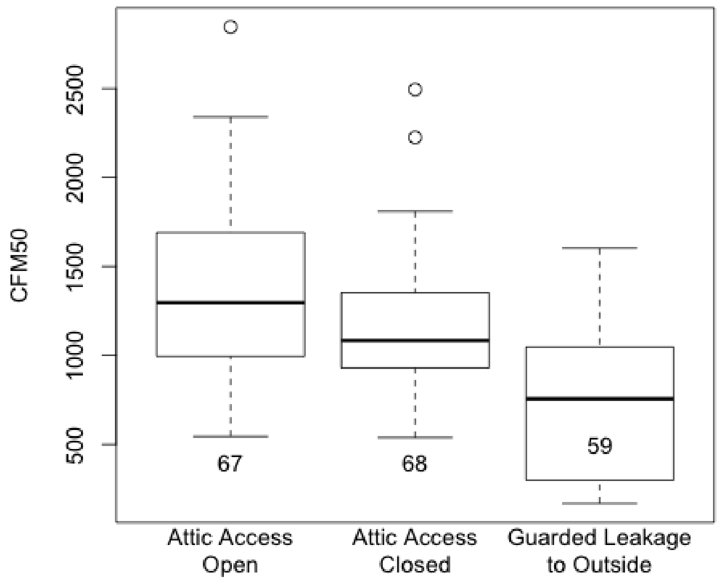

Figure 6 Boxplot summaries of whole house airtightness tests in sealed and insulated attic homes, with attic access hatch open and closed.

Median whole house airtightness in sealed and insulated attic homes in this sample was 2.1 ACH_{50}, which is substantially more airtight than typical new homes. This was mostly the result of the 20 homes measured by Hoeschele et al. (2015), which included very airtight new homes insulated with ocSPF. Most other research did not report ACH_{50} values.

Nearly all testing in sealed and insulated attic homes comes to the same conclusion: sealed and insulated attics remain somewhat leaky to both outside and the house, and they are likely leakier than the houses they are attached to when normalized by surface area. They are almost always more connected with the house than with outside. In cases where attic leakage to outside was isolated from house leakage, the proportion of whole house leakage located in the attic varied from 21 to 85%, with a median of 52%. Attic air leakage was dramatically lower in the modern homes reported in Hoeschele et al. (2015), with median attic air leakage to outside of 246 versus 921 cfm_{50} for the homes in previous research. This may not be a generalizable finding to all new homes, as the builder had extensive experience with this attic type in thousands of homes. While we do not know the relative proportion of envelope surface area in these homes, it seems likely that “sealed and insulated” attics have leakier construction (normalized by surface area) than the houses they are attached to. Consistent with this, zonal pressure testing suggest that on average house ceiling planes provide about 34% of the pressure drop during a depressurization test, while the roof plane provide the remaining 66%. At worst, the connection between the house-attic and attic-outside were equivalent in this sample (ΔP of 27pa). Rudd (2005) reported that ceiling plane airtightness was highly variable, due to varied ceiling penetrations (e.g., recessed lights, ventilation fans, etc.). Furthermore, as discussed below, the thermal behavior of sealed and insulated attics suggests they are more coupled to the house than to outside, though to varying degrees.

While they did not report measurement data from the four homes they tested, Siegel & Walker (2003) came to the same conclusions, namely that: (1) attics were as leaky to outside as to the house and (2) unintentional venting area was approximately 1 ft^2 per 500 ft^2 of roof surface area (Siegel & Walker, 2003). Field personnel reported unfamiliarity and difficult in sealing attics.

Due to missing data and small sample sizes, no relationships in airtightness were discernible by climate zone or insulation/air sealing method (i.e., spray polyurethane foam (SPF) versus fibrous insulation). Alternatively stated, it is clear that sealed and insulated attics insulated with fibrous insulation can achieve similar airtightness levels to those insulated with SPF.

Type of Test	Metric	Minimum	Median Value	Maximum	n
Guarded Test	Attic Leakage To Outside (cfm_{50})	168	756	1602	59
Guarded Test	Percent of Total House Leakage Through Attic to Outside (%)	21%	52%	85%	56
Single Blower Door	Whole House Leakage - Attic Access Open (cfm_{50})	545	1296	2846	67
Single Blower Door	Whole House Leakage - Attic Access Closed (cfm_{50})	538	1083.5	2494	68
Single Blower Door	Difference in Whole House Leakage, Attic Access Open vs. Closed (cfm_{50} (%))	1 (0%)	182 (13%)	484 (28%)	66
Single Blower Door	Whole House Leakage (ACH_{50})	1.46	2.08	10.1	27
Single Blower Door	ΔP Attic WRT House, House at -50pa (pa)	7	17	27	46

Table 5 Summary of sealed and insulated attic airtightness testing reported in the literature.

6.5 Measured Airtightness of HVAC Distribution Ducts in Sealed and Insulated Attics

Reported measurements of air leakage in HVAC distribution ducts located in sealed and insulated attics were assembled from five difference sources for a total of 40 homes (GARD Analytics, Inc., 2003a; Hoeschele et al., 2015; Rudd & Lstiburek, 1996; Sherman & Walker, 2002; Siegel & Walker, 2003).

Across all homes (and consistent with the sealed and insulated attic airtightness data presented above), HVAC ducts in sealed and insulated attics remained relatively leaky, with total leakage varying from 5 to 16% (median of 8%, n=24). It is important to remember that in sealed and insulated attic homes, the majority of this total leakage is within the conditioned volume, and it serves to condition the attic air and mix it with the house volume. Yet, Pallin et al. (2013) have reported that changing duct leakage in sealed and insulated attics from 4 to 20% can increase space conditioning energy demand by 5 to 15% (with high climate variability). Total system leakage to outside averaged 1% (from 1 to 6%, n=24). Older and newer homes differed sharply on how much of the total leakage was to outside the envelope, largely due to more airtight construction of the attic roof surfaces themselves in the newer homes (i.e., those reported by Hoeschele et al. (2015)). Whereas 55% (from 0 to 82%, n=20) of total leakage was to outside in the older set of sealed and insulated attic homes, only an average of 16% (from 6 to 32%, n=20) was to outside for the new homes. This supports the notion that overtime the industry has gained experience and skill in implementing successful, airtight sealed and insulated attics. The total duct leakage median was 101 cfm (from 28 to 302 cfm, n=40), with 21 cfm of duct leakage to outside (0 to 167 cfm, n=40).

It is noteworthy that many of these measurements are from homes built prior to inclusion of duct airtightness requirements in California's Title 24 building energy code. In general, we would expect new homes built to California Title 24 to have lower total duct leakage, as well as lower leakage to outside. This is consistent with the measurements for new California homes reported by Hoeschele et al. (2015).

Measurements in new California homes with traditional vented attics provide a further point of comparison for thinking about leakage rates in sealed and insulated attics. Unfortunately, reported measurements provide inconsistent results. Wei et al (2014) briefly summarize the 4,161 duct leakage measurements from the CHEERS database of a sample of new California homes built in 2012 (Wei et al., 2014). According to their reported data, all homes met the 6% duct leakage requirement, and more than half of the homes had 5% or less of nominal air handler airflow, and just over 20% of homes were 4% or less. Others have reported contrasting results. For example, measurements in 43 single family new California homes built in 2007 were reported by Proctor et al. (2011), and while no summary statistics are provided, figures suggest that a substantial minority of homes failed to meet the 6% leakage criteria (median was below 6%). A few homes failed very badly (leakage 10-25%), and a larger subset of homes were close to passing (6-9% leakage). Almost all homes had ducts in the vented attic, and accordingly leakage to outside made up the vast majority of total leakage in most homes. Again, no summary statistics are reported, but it appears that leakage to outside was at least 50% and more typically 80 to 90%. They found median airflow imbalances between supply and return ducts of 17% (Proctor et al., 2011). Similarly, Offermann (2009) measured forced air unit duct leakage in 138 new California homes and reported median leakage rates of 10% (from 2 to 73%). 86% of the tested homes (119) exceeded the code requirement of 6% leakage or less, and on average these homes had 70% more leakage than allowed (i.e, 10% leakage).

6.6 Observed Construction Defects

Common sense suggests that maintaining a continuous air barrier in a sealed and insulated attic is problematic at penetrations, framing intersections, corners, etc. just as is the case with other building assemblies. Based on inspections of construction defects and in provision of quality assurance to efficiency programs, authors from IBACOS identify and provide example images of the following common crack types in sealed and insulated attics: (1) plumbing penetrations, (2) foam delamination from framing, (3) framing intersections, (4) ridge vent sealing and (5) poorly sealed soffit vents in existing homes (Prahl & Shaffer, 2014) (see example images in Figure 7 and Figure 8). Consistent with this, thermographic inspection of a sealed and insulated attic in a Houston, TX home, showed evidence of air leakage around gas appliance exhaust and intakes. Roof peaks had no sign of leakage, but leakage often occurred at transitions and connections between roofs and walls, especially at complicated areas with multiple intersecting planes, namely roof-wall connections, dormers and gable ends (Ueno & Lstiburek, 2015). Siegel & Walker (2003) noted poor attic air sealing due to difficulty in getting crews used to new activities and a lack of oversight/inspection. Another example of difficult construction for air sealing has been identified in the first test house for the CEC study that this literature review is being prepared for. A problematic detail was already identified where continuous sheathing extends across the entire main roof, and then an intersecting sub-roof is simply attached on top of that. This is a problematic area to seal and insulate, requiring special engineering, framing and attention to detail.

Figure 7 Example image of closed cell SPF delamination from roof framing member. Source: Prahl and Shaffer (2014).

Figure 8 Example picture of gaps surrounding roof vent pipe penetrations. Source: Prahl and Shaffer (2014).

6.7 Performance Criteria

No attic airtightness criteria are included in the International Residential Code 2012 or in the U.S. DOE Building America Measure Guideline for Sealed and insulated Attic Insulation. We are unaware of any other programs that use an attic-specific airtightness requirement. The Prescriptive Package-A, Option C in the 2016 California Title 24 Building Energy Code requires that HVAC system leakage to outside be less than 25 cfm when ducts are counted as in conditioned space, but these are vented attic constructions.

The only discussion of airtightness criteria for sealed and insulated attics comes from Rudd (2005), in which their preferred criteria is 0.25 cfm_{50} per square foot of building surface area (cfm_{50}/ft^2SA). This is the same criteria they suggest for whole house airtightness in the Building America program. Based on initial measurements in 10 California homes, they postulated a requirement for less than 20% difference between whole house airtightness with attic access open and closed (or less than 17pa attic WRT house). But further testing in 33 California and Arizona homes suggested this criteria was untenable due to unpredictable differences in ceiling plane airtightness, resulting from ceiling penetrations for lighting and other services. 17 houses that passed the 0.25 cfm_{50}/ft^2SA test would not have passed the attic ceiling pressure difference criteria. They also performed two-blower door guarded tests to assess attic leakage to outside, but they concluded that it was labor-intensive and did not show consistency in providing "sealed and insulated" qualification criteria that was coherent relative to the other tests. They conclude that thermal conditions in sealed and insulated attics did not vary consistently with levels of airtightness, so they recommend the single attic access open envelope leakage test, with criteria of 0.25 cfm_{50}/ft^2SA applied to the whole building, including the house and attic.

6.8 Testing Recommendations

The appropriate testing configuration depends on the goals of the airtightness test. For example, if trying to assess the construction quality and the relative leakiness of the attic surfaces compared with the house surfaces, then testing with the attic access open is desirable. If, on the other hand, energy or ventilation estimates are being made, the house should be tested in its standard configuration, with the attic access closed. If the attic and house are both airtight, then the measured leakage should be very similar in either configuration. The same goes for duct airtightness testing. If one needs to know the air leakage into the conditioned attic (e.g., for purposes of mixing or partial conditioning), then total leakage testing is appropriate. On the other hand, an energy simulation tool will need to know the duct leakage to outside in order to provide accurate energy consumption estimates.

7 Thermal Performance of Sealed and Insulated Attics

When considering the thermal performance of sealed and insulated attics, one must consider the thermal conditions of the roof assembly—shingles and sheathing—as well as the conditions in the attic volume itself. These thermal conditions are addressed individually in the sections below, and the existing literature is summarized for these elements in Table 6.

We draw the following conclusions from the literature:

- Past field measurements suggest that temperatures in sealed and insulated attic volumes are well coupled to the house volume, an effect seen whether the ceiling plane is airtight or leaky. We expect even tighter coupling of the attic and house volumes under two conditions: (1) with direct conditioning (i.e., using intentional supply of heated or cooled air to the attic volume), and (2) as sealed and insulated attics become more thermally insulated and airtight (compared with older sealed and insulated attics, which were often leaky and inadequately insulated).
- It is extremely rare for the sealed and insulated attic volumes to be more than 10°F (5.6°C) above or below the house temperature in hot-dry climate regions.
- Sealed and insulated attics are generally warmer than the house during summer and cooler than the house during winter.
- Peak roofing shingle temperatures (upwards of 180°F (82°C)) can be approximately 20°F (11.2°C) higher over sealed and insulated attics than over vented attics, but typical differences (sealed and insulated – vented) are 3 to 7°F (1.7 to 3.9°C), and long-term average differences are very small (<1°F (0.5°C)). Peak roof sheathing temperatures are elevated in sealed and insulated attics, typically by 16 to 17°F (9 to 9.5°C).
- The solar properties, presence of above-sheathing ventilation, and thermal mass of roof assemblies strongly influence attic/roof thermal performance. The effects of these parameters on attic air temperature and HVAC system energy use are often greater than those predicted or observed for sealed and insulated attic approaches. The benefits of a sealed and insulated attic strategy are expected to increase when coupled with cool roof and other advanced strategies (e.g., above-sheathing ventilation and thermal mass).

When compared with conventional vented attics, sealed and insulated attics often behave in opposite ways. Attic volume temperatures closely track the house temperature in sealed and insulated attics, whereas attic temperatures generally track outside temperatures when vented. This makes the vented attic hotter in summer and colder in winter. So, under both heating and cooling demand, the sealed and insulated attic provides a milder environment for the HVAC system. When considering the roof deck assembly, the sealed and insulated attic generally experiences more extreme high temperature conditions (see Figure 9 for an example of roof sheathing temperatures in an sealed and insulated attic home). This is because the insulation on the underside of the roof sheathing slows the rate of heat transfer from the higher temperature roof assembly into the lower temperature attic—this leads to higher assembly temperatures.

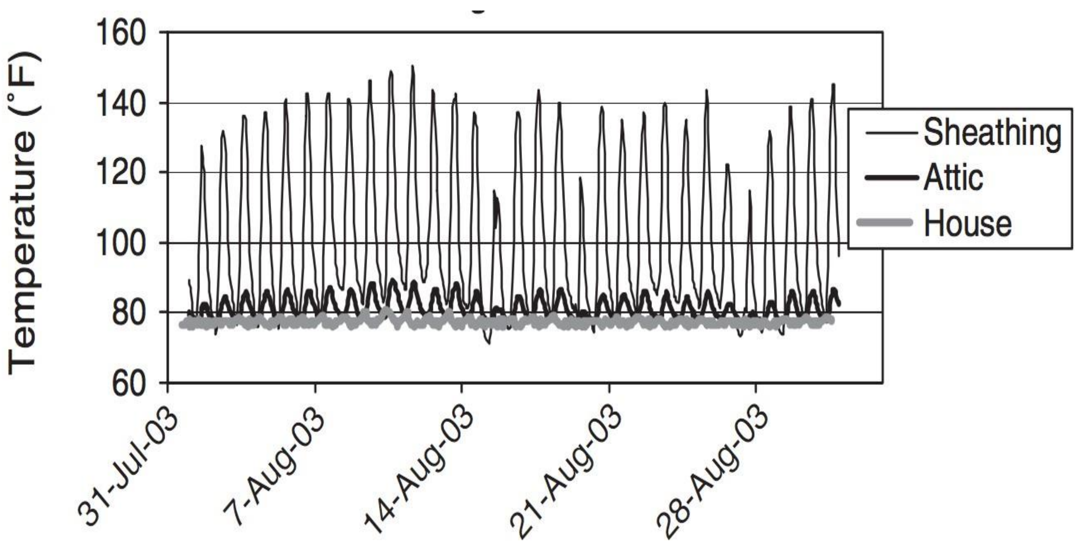

Figure 9 Time series plot comparing bottom of roof sheathing, attic air and house volume temperatures in a sealed and insulated attic home in Peoria, AZ (August 2003). Source Rudd (2014).

As would be expected, vented and sealed and insulated residential roofs and attics experience the hottest temperatures during the summer, when the south-facing roof slope is generally the warmest. This is due to increased solar gains. These assemblies experience the coldest temperatures during the winter, with the north-facing slope generally the coldest. In both cases, this is due to the difference in solar exposure of the north and south slopes. Research has consistently found the north-facing roof sheathing to be the coldest surface in sealed and insulated roof assemblies, increasing the possibility of condensation. As a result, assessments of moisture damage tend to focus on the north-facing surfaces.

Furthermore, we are unaware of any research documenting thermal conditions in the advanced attic approaches contained in California Title 24 Prescriptive Package-A, Options A, B and C. These are all vented attic options, but they differ substantially from traditional vented attics. For example, Option C—ducts in conditioned space (DCS)—uses a traditional vented attic that from a thermal point of view does not contain ducts. This will lead to more extreme temperatures, because thermal losses from the HVAC system no longer contribute to the partial conditioning of the space. So, the attic will be hotter in summer and colder in winter. This strategy reduces duct thermal losses, but it exacerbates thermal losses between the attic volume and house. The high performance vented attic options in Title 24 (Options A and B), use insulation at the roof deck to reduce heat flux across the roof assembly. This should lead to cooler attic temperatures during the cooling season and unclear changes in attic temperature during the heating season.

Source	***House Descriptions***	***Findings***
Rudd & Lstiburek, 1996	2 sealed and insulated attics, 1 vented attic (1:150) in Las Vegas, NV	Max red roof tile temp increased 3°F(1.7°C) (max 132°F (55.6°C)) relative to vented attic (max 129°F (53.9°C)). Sheathing max by 16°F (9.0°C)(max of 125°F (51.7°C))
Rudd (2005)	9 sealed and insulated attics in Banning, CA	Cooling season: 95% of hourly ΔT (House to Attic) were between -2 and 6°F (-1.1 to 3.4°C). Max ΔT in any home was 10°F (5.6°C). Heating: 96% of hourly ΔT between -4 and 2°F (-2.2 to 1.1°C). Max ΔT in any home 6°F (3.4°C).
	4 Sealed and insulated attics in Phoenix, AZ	Cooling season hourly ΔT -2 to 8°F (-1.1 to 4.5°C). Peak roof sheathing temp of 150°F (65.6°C).
	1 sealed and insulated attic in Houston, TX, shingle roof	Diurnal sheathing temps between 70 and 170°F (21.1 to 76.7°C).
	1 sealed and insulated attic, 1 vented attic in Jacksonville, FL	Peak shingle temp of 180°F (82.2°C), max shingle ΔT of 7°F (3.9°C) (monthly avg 0 of 0.2°F (0°C)). Similar degree of stratification in vented/sealed and insulated, max stratification of 12°F (6.7°C) (avg 3°F (1.7°C)).
Hendron et al (2002)	1 sealed and insulated attic in Las Vegas, NV	Summer: sealed and insulated attic within 7°F of house (3.9°C), vented attic tracked outside temperature. Winter: sealed and insulated attic tracked interior temp very well, vented attic was approximately midway between house and outside.
Parker et al. (2002)	1 sealed and insulated attic home, 1 vented attic home, both dark shingles. Fort Meyers, FL	Peak avg attic temp of 83°F (28.3°C), house at 77°F (25°C). Shingle temp 7°F (3.9°C) hotter on average (avg max of 128°F (53.3°C)), sheathing temp was peak avg 20°F (11.2°C) hotter (136°F (57.8°C)). Peak shingle temp of 166 vs. 144°F in vented attic (74.4 vs. 62.2°C).
Ueno & Lstiburek (2015)	1 sealed and insulated attic in Houston, TX	Summer: attic generally warmer than house, more similar to house than to outside. Typical diurnal attic temperature cycle 73 to 81°F (22.8 to 27.2°C). Attic temps varied by orientation and attic height by 2°F in summer and 4°F (max) in winter (1.1 and 2.2°C).
Rose (1995)	Buildings Research Facility, central	Summer: sealed and insulated cathedralized peak sheathing temperature of 178°F (avg 88°F) (81.1°C (avg 31.1°C)), vented

	IL, cathedralized attic test roofs, vented, sealed and insulated, with/without air chute, kraft facing taped/untaped	cathedralized peak 169°F (avg 86°F) (76.1°C (avg 30°C)).
Rose (1992)	Buildings Research Facility, central IL. 5 cathedralized roof types assessed alongside 5 flat roof attics with/without venting	South orientations had highest temperatures. Maximum sheathing temperatures were highest in the cathedralized attics, from 170 to 186°F (76.7 to 85.6°C) (top of sheathing between plywood and tar paper). Vented, flat ceiling attic max sheathing temp of 165°F (175°F in flat not-vented) (73.9 and 79.4°C).
Miller et al (2013)	6 vented (R46) and 1 sealed and insulated (R22) attics in South Carolina test facility with varying roof/attic technologies	Sealed and insulated attic showed least diurnal attic temperature variation. In winter, sealed and insulated attic volume much warmer at night and similar during daytime hours. During summer, sealed and insulated attic was warmer at night and cooler during the day. Above sheathing ventilation and radiant barriers also reduced fluctuations in attic air temperatures.

Table 6 Summary of findings from temperature measurements in sealed and insulated attics.

7.1 Thermal Coupling with the House

The strong thermal coupling of sealed and insulated attics and their attached house volumes has been documented in a number of field studies. These have all occurred in homes where the attic acts as a partially conditioned buffer zone between the house and outside (i.e., there is no direct conditioning by HVAC supply). We would expect that with direct conditioning, the coupling would be even stronger, though this has not yet been demonstrated in the research.

Rudd (2005) reported on house and attic air temperatures for nine homes with sealed and insulated attics located in Banning, CA (see Figure 10). During the cooling season, 95% of hourly ΔT's (attic to house) were between -2 and 6°F (-1.1 and 3.4°C). None of the nine attics experienced a single hour over 90°F (32.2°C), and 99% of observations were below 84°F (28.9°C). The maximum ΔT in any home was 10°F (5.6°C) during the cooling season. In the heating season, 96% of hourly ΔT's were between -4 and 2°F (-2.2 and 1.1°C). None of the attics experienced a single hour below 52°F (11.1°C), and 99% of observations were above 60°F (15.6°C). The maximum ΔT in any home was 6°F in the heating season (3.4°C). They did not find any relationship between the coupling of the house and attic temperatures with the airtightness of the house-attic ceiling interface. Rudd also reported similar results for four homes with sealed and insulated attics in Phoenix, AZ, with cooling season hourly ΔT's between -2 to 8°F (-1.1 and 4.5°C). Hendron et al. (2002) reported adequate data for one home with a sealed and insulated attic in Las Vegas, NV and another vented attic home in the same location. During the cooling season, the sealed and insulated attic was within 7°F of house (3.9°C), and the vented attic tracked the outside temperature (see time series plot in Figure 11). During the heating season, the sealed and insulated attic tracked the interior house temperature very well, and the vented attic was approximately midway between the house and outside. Ueno & Lstiburek (2015) reported on one home with an sealed and insulated attic in Houston, TX, and during the cooling season, the attic was generally warmer than house, but more similar to the house than to outside. Typical diurnal attic temperatures cycled between 73 and 81°F (22.8 to 27.2°C).

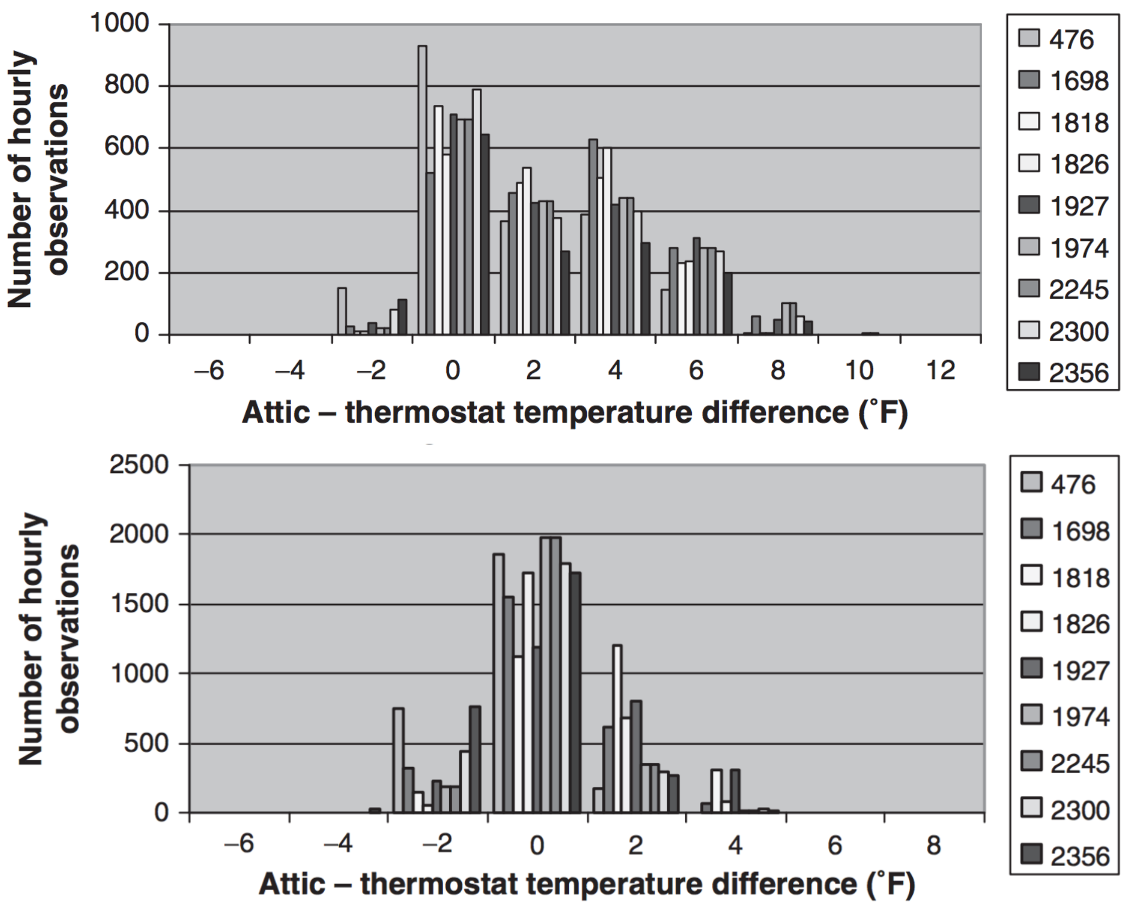

Figure 10 Histograms showing heating (lower plot) and cooling season (upper plot) distributions of measured differences between living space and sealed and insulated attic volumes in nine California homes. *Source: Rudd (2005)*.

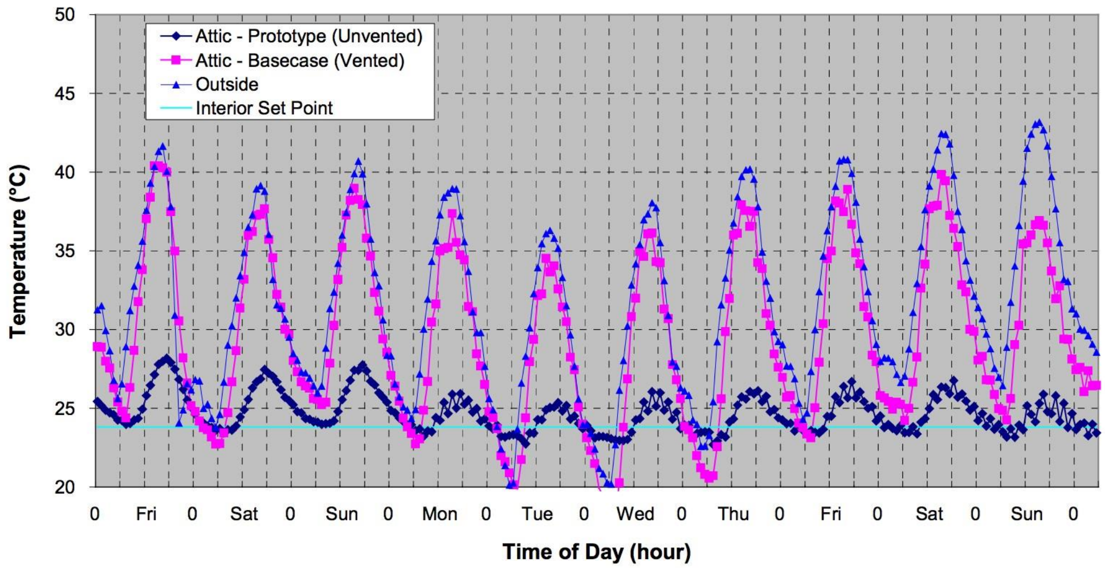

Figure 11 Time series plot of attic volume and outside temperatures for comparable vented and sealed and insulated attic homes, Las Vegas, NV. ***Source: NREL/Hendron et al (2002)*.**

As expected, measured sealed and insulated attic temperatures are consistently similar to the house temperatures, with somewhat more variability during the cooling season, likely due to strong solar effects. Sealed and insulated attics are generally warmer than the house during summer and cooler than the house during winter. It is safe to say that in a sealed and insulated attic in a hot-dry climate, it is very rare for the temperature to stray more than 10°F from the house temperature.

Variability in the degree of thermal coupling is likely the result of the levels of thermal insulation used and achieved airtightness of the attic relative to the house and outside. For sealed and insulated assemblies with lots of leakage to outside and lower insulation (i.e., R-19 or R-22), we would expect the attic to be mid-way between the house and outside. While they did not report measured attic temperatures, Siegel & Walker (2003) measured HVAC delivery efficiency was the same in vented and sealed and insulated attics, and this was attributed to low (R-19) insulation levels in the attics and the poor air sealing of the attics. Whereas for a highly insulated and airtight attic, with substantial communication with the house, we expect tight thermal coupling with the house.

7.1.1 Air Temperatures in Vented Attics

What was not generally reported in the research summarized above was any comparison with attic temperatures in vented attics, which also behave differently depending on the season. For example, during the afternoon in the cooling season, the vented attic temperatures are often greater than the ambient outside temperature, due to radiant heat gain from the solar heated roof deck. In the heating season, heat losses from the house tend to increase the attic volume temperature relative to outside.

Both of these phenomenon are illustrated in the summary Walker (1998) provides of measurements of vented attic and outside ambient temperatures in heating and cooling seasons made in 24 Florida homes, in two research homes in Alberta and in the University of Illinois Building Research Laboratory (a multi-roof testing facility) (Walker, 1998). Design condition (2.5%) temperature differences between well-vented attics and outside varied from 16 to 22°F in the cooling season (9.0 to 12.3°C), and from 9 to 11°F in heating season (5.0 to 6.2°C). Poorly vented attics experienced higher cooling season temperature differences, ranging from 27 to 36°F (15.1 to 20.2°C), and 13°F in the heating season (7.3°C). Rose (1992) measured peak vented attic temperatures that exceeded the peak ambient temperature by at least 28°F (15.7°C) for a white shingled roof and 32°F (17.9°C) for a dark shingled roof. Similarly, Parker & Sherwin (1998) measured vented attics in their Flexible Roof Facility in Florida with a variety of vent areas and roof finish colors, and they found that all vented attics experienced peak summer attic temperatures substantially above the ambient outside peak (97°F vs. 122 to 142°F) (36.1 vs. 50.0 to 61.1°C) (Parker & Sherwin, 1998a). So, while vented attics are hotter than ambient during cooling periods, sealed and insulated attics are cooler than ambient, making their benefit even greater. In the heating season, vented attics are generally warmer than ambient, though not as warm as sealed and insulated attics, both providing some protection for HVAC distribution equipment located in the attic.

7.2 Thermal Stress on Roof Assembly

One concern about roof assembly durability in sealed and insulated attics, is that roof finish materials will experience much higher average and peak temperatures. Findings on the temperature of roof claddings (e.g., asphalt shingles, roof tile) and sheathings have been mixed in the literature. Rose (1995) reported peak top of sheathing temperatures (akin to shingle temperatures) above 180°F (82.2°C) for several cathedralized ceilings (max 186°F (85.6°C)), whereas the flat ceiling, vented attic peaked at 165°F (73.9°C)—a full 21°F lower (11.8°C) (Rose, 1995). Parker et al. (2002) reported a similar 22°F (12.3°C) difference in peak dark shingle temperatures on vented and sealed and insulated attics of 144 vs. 166°F (62.2 vs. 74.4°C). Yet, this same paper reported that the *average* peak shingle temperature was only 6°F (3.4°C) greater in the sealed and insulated attic (128 vs. 122°F (53.3 vs. 50.0°C)), and the average peak sheathing temperature was 17°F (9.5°C) greater in the sealed and insulated attic (118 vs. 135°F (47.8 vs. 57.2°C)) (Parker, Sonne, & Sherwin, 2002). Rudd (2005) reported on measurements in one vented and one sealed and insulated attic homes in Jacksonville, FL, and they found a maximum shingle temperature of 180°F (82.2°C), but with a maximum difference of only 7°F (3.9°C) between vented and sealed and insulated, and a monthly average difference of only 0.2°F (0.1°C) (see Figure 12 for detailed distribution of temperature differences). Rudd (2005) also reported on four sealed and insulated attic homes in Phoenix, AZ and another in Houston, TX, whose peak sheathing temperature was

150°F and 170°F (65.6 and 76.7°C), respectively (Rudd, 2005). Rudd & Lstiburek (1996) reported on two sealed and insulated attic homes and one vented attic home in Las Vegas, NV, and the maximum temperature for the red roof tile was 3°F (1.7°C) hotter in the sealed and insulated attic homes (132 vs. 129°F (55.6 vs. 53.9°C)), but the sheathing maximum temperature was 16°F (9.0°C) greater in the sealed and insulated attic homes (max of 125°F (51.7°C)) (Rudd & Lstiburek, 1996).

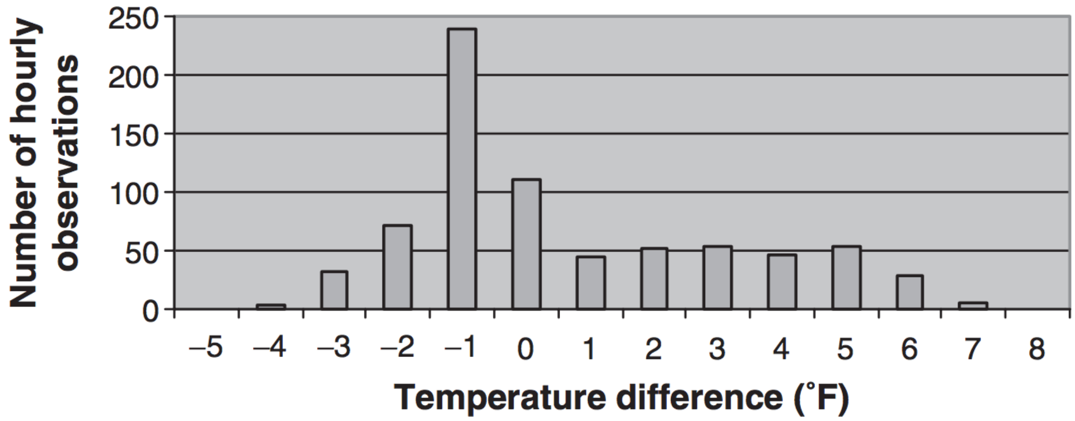

Figure 12 Histogram showing distribution of roof shingle temperature differences over a single vented and sealed and insulated attic in Jacksonville, FL (August 2001). ***Source: Rudd (2005)*.**

While these findings are somewhat mixed, and it is not always perfectly clear what metrics are being reported, the following can be concluded. Extreme peak shingle temperatures (upwards of 180°F (82.2°C)) can be approximately 20°F (11.2°C) hotter on sealed and insulated vs. vented attics, but typical peak temperature differences are more along the lines of 3 to 7°F (1.7 to 3.9°C), and long-term average differences are very small (<1°F (<0.6°C)) (see Figure 12 for an example). Peak sheathing temperatures (measured on the underside of the sheathing) appear to be more consistently elevated in sealed and insulated vs. vented attics, with typical peak temperature differences of 16 to 17°F (9.0 to 9.5°C). Furthermore, variations in roof cladding have a strong impact on this effect, with cool roof surfaces and vented tile finishes leading to lower assembly temperatures (as discussed in Section 7.3).

In general, we conclude that this issue is not of major concern. Peak and average shingle temperatures are also affected by varying location in the U.S., as well as by roof color, solar properties, orientation and roof slope. These effects are often greater than those associated with sealed and insulated roofs. Furthermore, an investigation by the National Roofing Contractors Association suggests that numerous shingle manufacturers continue to warranty installations over sealed and insulated, conditioned attics, with certain limitations (Graham, 2008).

7.3 Variations with Roof Construction

Attic and roof thermal performance varies substantially with changes to roof system solar properties (solar emittance and solar absorptance), thermal mass and roof deck ventilation. Cool roof surfaces change the absorptance and reflectance of incoming solar radiation, generally leading to lower roof temperatures and heat flux. Tile roof systems benefit from the heat buffering provided by the thermal mass, as well as from generally better solar properties, and in some cases, roof deck ventilation (i.e., air flows under the back of the tile), either due to the tile shape (medium or high profile tiles) or to installation on top of wooden battens. Metal roof finishes can include cool color surfaces, as well as incorporate roof deck ventilation. All of these approaches have been shown to provide lower roof assembly temperatures and reduce heat flux across the roof under cooling conditions. Typically, cool roofs are associated with a heating energy penalty, because of their ability to reject incoming solar energy, which would otherwise warm the attic air volume.

In a vented attic context, these approaches can, at best, bring the attic volume into approximate thermal equilibrium with the ambient outside air. Though thermal losses from duct systems located in attics, as well as attic heat loss to the cooled house volume, might lead the attic air temperature to be below outside ambient conditions during cooling. In a sealed and insulated attic context, heat flux across the roof is already being reduced by the placement of insulation, but the assembly experiences extreme conditions, as documented above. Use of these strategies in conjunction with sealed and insulated attics will further improve their performance, and lessen the thermal stress on the assembly.

7.3.1 Cool Roofs

Cool roofs are the most well studied of these approaches to roof construction, with nearly all research focused solely on vented attic constructions. Cool roof finishes reduce roof surface and assembly temperatures, reduce attic air temperatures, and have been shown to reduce energy use in cooling dominated climates. The research supporting these benefits is summarized below. This rejection of incoming solar energy also leads to lower roof assembly and attic air temperatures during the heating season, which can negatively affect heating energy use, and can also lead to increased likelihood of moisture accumulation in sheathing. Miller & Kosny (2008) used simulations of attic performance to suggest that provision of roof deck ventilation eliminated this heating energy penalty. These issues are discussed in the energy performance and moisture sections of this review.

California's 2013 Title 24 Building Energy Code currently includes prescriptive cool roof requirements in certain instances for residential new construction (California Energy Commission, 2012) (see Table 7). Wray et al. (2006) proposed and supported these requirements through simulations and a review of the cool roofs literature (Wray, Akbari, Levinson, & Xu, 2006). Updated requirements in the 2016 version of Title 24 were summarized in Section 4.1.3.2.

	CA T24 Climate Zones	Min 3-Year Aged Solar Reflectance	Min Thermal Emittance	Min Solar Reflectance Index (SRI)
Low-Slope	13 & 15	0.63	0.75	75
Steep-Slope	10-15	0.2	0.75	16

Table 7 California Title 24-2013 prescriptive cool roof requirements for low-rise residential roofs, new construction.

Cool roof surfaces lead to lower roof surface and roof assembly temperatures (Parker & Barkaszi, 1997; Parker et al., 2002; Rose, 1992). Rose (1992) reported a maximum sheathing temperature 17°F (9.5°C) cooler for vented white shingles versus vented dark shingles (Rose, 1992). Parker & Barkaszi (1997) reported preliminary test results for a single family Florida home whose roof reflectance was increased from 0.22 to 0.73, and whose daytime roof surface temperature was reduced from 160 to 171°F down to 109°F (71.1 to 77.2 down to 42.8°C). Parker et al. (2002) reported on measurements in seven roofs on unoccupied side-by-side residences in Florida, and average peak roof surface temperature was 11 to 28°F (6.2 to 15.7°C) cooler on white finished roofs. The white shingle finish was an exception, with peak surface temperatures similar to non-white finishes.

Cool roof surfaces also lead to lower attic air temperatures (Parker & Sherwin, 1998a, 1998b; Parker et al., 2002). For example, Parker & Sherwin (1998b) measured summertime temperatures in 21 Florida attics, and seven attics with white finish roofs had 2.5% design condition temperature differences of -1.5°F (-0.8°C) (attics cooler than ambient, from -9 to 8°F (-5.0 to 4.5°C)), whereas ten vented attics (soffit and ridge venting) with a variety of shingle colors averaged 22°F (11.2°C) hotter than ambient at 2.5% design conditions (from 19 to 27°F (10.6 to 15.1°C)). Shingle roofs with only soffit venting had substantially higher temperature differences, averaging 36°F (20.2°C) (from 32 to 41°F (17.9 to 23.0°C)). A single tile roof had a design temperature difference of 10°F (5.6°C). Parker & Sherwin (1998a) reported on measurements of seven vented roofs at the FSEC Flexible Roof Facility (FRF), and they found that white finish roofs dramatically reduced attic air maximum temperatures from 122 - 142°F (50.0 - 61.1°C) (for dark shingle and red tile roofs) to 96 and 107°F for white tile and metal roofs, respectively (35.6 and 41.7°C). Mean attic air temperatures were 5 to 10°F (2.8 to 5.6°C) cooler in the white finish roof attics. As a result, attic air relative humidity was highest in attics with white roof finishes. Similarly, Parker, Sonne, & Sherwin (2002) measured average peak attic temperatures in seven unoccupied Florida homes, and the white finish tile and metal roofs had average peak average temperatures just slightly greater than the sealed and insulated attic (83°F versus 88 to 92°F (28.3 versus 31.1 to 33.3°C)) (see plot of peak-day attic air temperatures in Figure 13).

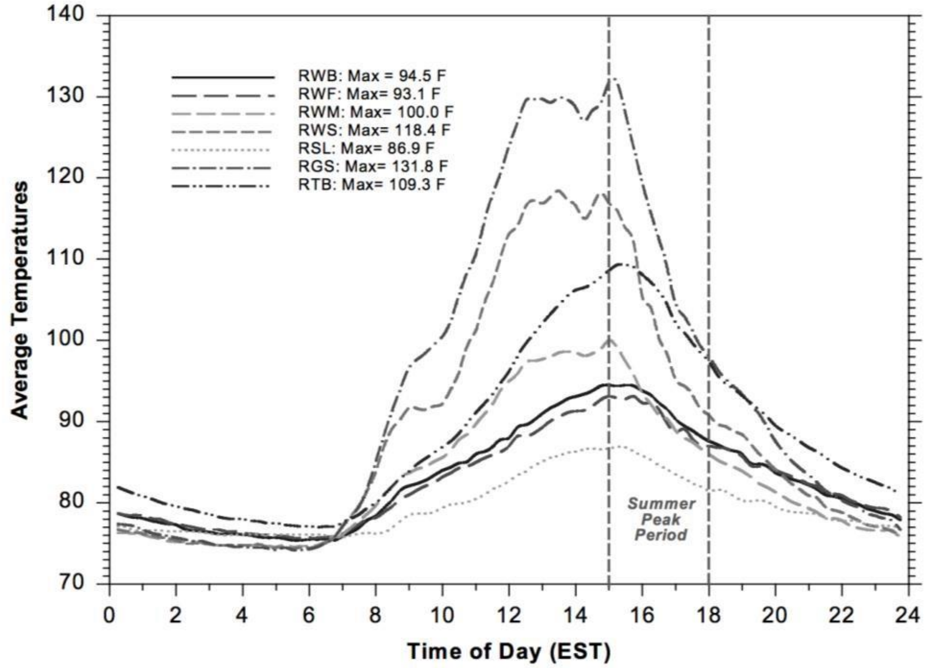

Figure 13 Comparison of attic air temperatures over the course of a peak-cooling day (July 26, 2000) ***Source: Parker, Sonne and Sherwin (2002).***

Finally, cool roof surfaces have been shown to reduce cooling energy use in Florida homes (Parker & Barkaszi, 1997; Parker et al., 2002). Parker & Barkaszi (1997) whitened nine roofs on occupied homes in Florida in mid-Summer providing a before and after control for each home. Average cooling energy savings were 19% (from 2 to 43%). Savings depended on initial ceiling insulation levels, roof solar reflectance, air duct location and cooling system size. Peak savings similarly averaged 22%. Parker et al. (2002) reported on monitoring in seven Florida homes and showed that highly reflective roofing provided 19-24% cooling energy reductions and peak demand reductions of 28-35% (0.8 to 1 kW).

7.3.2 Tile Roofs

Tile roofs experience lower thermal stress than conventional shingle roofs for a variety of reasons: (1) they are generally lighter in color and therefore have high solar reflectance and low absorptance, (2) they are often back-vented, either due to the shape of the tile or to installation on top of battens and (3) tile roofs contain substantial thermal mass which acts as a thermal buffer, and tends to reduce heat flux and peak temperatures. To illustrate, Beal and Chandra (1995) predicted reductions of 48% in roof deck heat flux for vented S-tiles on counter-battens (relative to black shingles), and a 39% reductions for direct nailed tile installations. More recently, Miller & Kosny (2008) reported on tests of various tile roofing materials (e.g., flat concrete tile, high- and medium-profile clay and concrete tiles) at their Envelope System Research Apparatus (ESRA). They found that relative to a reference dark colored shingle, flat, sealed and insulated concrete tiles reduced roof heat flux by 55%, showing the effects of the tile's thermal mass. Medium profile tiles, with and without cool roof coatings, had further reduced heat flux. Finally, they placed 1.25" of extruded polystyrene beneath a high profile clay tile with cool color finish, and found a 90% reduction in heat flux at solar noon. Notably, reductions in roof heat flux do not translate in a straightforward manner to cooling energy savings. In fact, a substantial portion of the cooling load is not due to roof heat flux, so these reductions only relate to one component of residential cooling loads.

8 Moisture Performance of Sealed and Insulated Attics

8.1 Introduction to Moisture in Residential Attic and Roof Assemblies

There are many sources of moisture in a typical residential attic, including:

- Outside air
- House air
- Building occupants
- Construction materials
- Rain or other liquid moisture leaks

The primary moisture concern in residential attics is the accumulation of moisture in wood building assemblies, which are subject to biological growth, deterioration and failure under certain conditions. The Forest Products Laboratory's *Wood Handbook* provides extensive documentation of the moisture properties of wood, and discusses the control of wood moisture in buildings (Richard et al., 2010). Further detailed discussion of general moisture control in residential buildings is provided in the *Moisture Control Handbook* (Lstiburek & Carmody, 1991) and the more recent *Moisture Control Guidance for Building Design, Construction and Maintenance* (U.S. EPA, 2013). Moisture references for non-residential applications also cover many relevant moisture issues for homes (Harriman, Brundrett, & Kittler, 2001).

Moisture can be contained in wood as either free water (i.e., liquid water or water vapor in cell lumina and cavities), or as bound water (held by intermolecular attraction within cell walls). The moisture content of wood is the ratio of the mass of water in the wood to the mass of the same specimen of oven dry wood. Wood fiber saturation occurs around 30% moisture content, and this is the point at which wood cell walls are completely saturated with bound water, but no free liquid water exists. When exposed to only water vapor in air, wood comes to its equilibrium moisture content, which varies with temperature and relative humidity of the air. The maximum MC under these conditions is at wood fiber saturation. Wood in building assemblies is exposed to both long-term (i.e., seasonal) and short-term (i.e., diurnal) changes in ambient air humidity and temperature, which induce changes in the wood moisture content. These changes are typically gradual, and short-term fluctuations tend to influence only the wood surface. Contact with liquid water can lead to capillary action or wicking with associated rapid changes in wood moisture content, and the MC can exceed fiber saturation. Contact with liquid water occurs in building assemblies as a result of either rainwater leakage or surface condensation.

Moisture moves through building assemblies as a result of a variety of driving forces, namely differences in temperature, moisture content, vapor pressure, air pressure and capillary action. Moisture exchange between wood products and the air depends on the vapor pressure of the air, and the current amount of water in the wood material and its temperature. Differences in vapor pressure drive moisture through assemblies by diffusion. For example, given two materials at a fixed temperature, moisture will flow from the material with the greater moisture content (i.e., vapor pressure). Temperature differences also drive moisture through assemblies by diffusion. So, given two materials with the same moisture content, moisture will flow from the material that is at a higher temperature, because it has a higher equilibrium vapor pressure. Differences in air pressure move moist air through assemblies, which can carry moisture to surfaces with the potential to condense into liquid water. It is the complex, real world dynamics of temperature, material moisture contents and boundary conditions that determine the time varying movement of moisture through a building assembly.

Moisture transport mechanisms for sealed and insulated attic/roof assemblies include rainwater leakage, moisture condensation and diffusion. These are listed by decreasing levels of risk/importance. Rain intrusion and surface condensation are more problematic, because they deposit liquid water on the wood, which means its moisture content can potentially rise above fiber saturation, leading to potentially rapid degradation. Rainwater intrusion is threatening, because it brings sheathing above saturation almost immediately, as it is in contact with bulk liquid water. If an extended period is spent at or above saturation, material damage and surface mold growth can occur. Air movement through a building assembly can transport water vapor to a surface below the dew point temperature of the air, where condensation can occur and moisture can accumulate. The slowest of these moisture transport processes is diffusion, and it is generally considered the least problematic, because under diffusion only, wood moisture content is limited to the fiber saturation point. Built-in construction moisture is also of concern, but it has been found to consistently dry out over first years of service.

Moisture dynamics in building assemblies are largely driven by temperature dynamics, which occur diurnally and seasonally. All assemblies experience dynamics of wetting and drying, but with differing magnitudes. It is typical in simulations and field studies to see assembly moisture contents increase during the heating season and decrease during the cooling season. These same temperature- driven dynamics occur diurnally within a day, with nighttime leading to increased assembly moisture, and daytime driving that moisture out of the assembly, either into the attic air or to outside. Moisture is often found to "ping-pong" back and forth between the attic air volume and the attic building assemblies and construction materials on a daily basis.

In the presence of these moisture transport mechanisms, the hygrothermal risk of moisture damage to a building assembly depends on safe storage capacity of each component/material, as well as time-varying dynamics of wetting, drying and moisture storage/redistribution. In effect, these dynamics can only be known through detailed hygrothermal simulation or field measurements.

8.2 Moisture in Sealed and Insulated Attics

The moisture performance of sealed and insulated attics has received considerable attention in the research literature. Hygrothermal performance of sealed and insulated attics has been assessed through simulations, as well as through field research, including destructive inspections and monitoring in actual homes and roof test facilities. Two main lines of inquiry exist: (1) the potential for condensation and moisture accumulation to occur at cold roof sheathing surfaces during winter, most notably at the peak of the roof and on northern exposures; and (2) moisture performance of sealed and insulated attics in hot-humid climates, namely the tendency for unacceptable attic air relative humidity (near saturation) during peak incident solar periods.

We draw the following conclusions from the literature:

- The primary moisture concern in residential attics is the accumulation of moisture in wood building assemblies, which are subject to biological growth, deterioration and failure under certain conditions. Concern is highest at the underside of the structural roof sheathing, where moist indoor air can contact the cold sheathing surface. This sheathing surface temperature is called the 'first condensing surface temperature', and preferably it should be kept above the dew point temperature of the attic air. Sheathing surface temperatures decrease due to cold outside temperatures, as well as due to radiative heat loss to the night sky.
- The following factors increase moisture risk at roof sheathing surfaces over sealed and insulated attics:
    - Increased indoor or outdoor humidity
    - Lower outdoor winter temperatures and higher levels of night sky radiation
    - North-facing roof slopes
    - Proximity to the roof peak
    - Use of air permeable insulation
    - Use of cool roof surfaces or radiant barriers
    - Increasing vapor permeability of insulation (maybe)
- To reduce moisture risk, the first priority should be elimination of paths for bulk water intrusion from outside. Once bulk water is controlled, the primary means for controlling moisture levels in sealed and insulated attic roof

assemblies are: (1) controlling the first condensing surface temperature, typically through use of continuous exterior insulation or air impermeable insulation in the roof rafter assembly; or (2) control of indoor moisture levels, typically through moisture removal by continuous whole house and intermittent local exhaust ventilation. Supplemental dehumidification or direct conditioning[14] of the sealed and insulated attic volume may be necessary in some cases, generally in hot-humid climates. Other proposed methods to reduce moisture risk include use of vapor permeable diffusion caps at roof peaks, enhanced roof deck ventilation and increased mixing of attic and house air volumes.

- Sealed and insulated attic/roof assemblies should strike a balance between their ability to limit wetting and to allow drying. The ability of an assembly to safely store and redistribute moisture is also important.
- Assessments of sealed and insulated attic assemblies at the design stage can be performed using hygrothermal analysis tools (i.e., WUFI), along with the criteria in ASHRAE Standard 160. The standard stipulates that to reduce mold risk, 30-day running average surface relative humidity should be below 80% when 30-day running average temperature is between 5 and 40C°. Time-dependent mold index modeling and thresholds are likely to replace this simple criterion in the near future.
- Total roof failures that require large-scale interventions (e.g., full re-roofing and sheathing replacement required) are rare, with the only example seen in this literature review involving installation of closed cell spray polyurethane foam (ccSPF) over wet roof sheathing.
- Field observations of problematic moisture conditions in sealed and insulated attics (e.g., condensation and dripping moisture) are more common. These have been reported in cold, mixed- and hot-humid climate zones. One example was reported for a California home (unknown location). These moisture issues are far and away most common in cases where fibrous insulation is used, generally near the roof peak.
- The dynamics of time-varying wood moisture content (MC)[15] and temperature determine moisture risk. Risk varies across different materials, with untreated lumber generally most susceptible to damage. The longer an assembly is at high MC (i.e., >30%), the more likely damage is to occur. Typically mold growth is inhibited at surface relative humidities below 80%. The risk of mold growth on wood also varies with temperature. Cold temperatures inhibit biological growth, making mold growth during cold winters unlikely, even if moisture accumulation occurs. Drying of seasonally stored moisture should proceed quickly to reduce risk of mold growth, because rising temperatures in the spring bring about conditions amenable

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[14] Air leakage from ducts located in sealed and insulated attics already provides some level of direct conditioning, albeit inadvertent.

[15] Wood MC is represented as a mass-fraction value, and it is the ratio of the mass of water in a sample of wood versus the mass of the same sample after oven drying.

to mold growth. Short periods of high MC are acceptable, as long as drying proceeds quickly, and there is no net-accumulation of moisture year-on-year.

- Moisture conditions in the attic air, attic framing and roof assembly can vary substantially on daily and seasonal bases. For example, attic air humidity commonly approaches saturation (i.e., 100% relative humidity) during summer afternoons in hot-humid regions, because solar gains drive moisture stored in the attic materials into the air, which is at a lower vapor pressure. The MC of materials in sealed and insulated roof systems can also vary widely on a seasonal basis (e.g., from 4 to 25%), making the time of any diagnostic measurements important.
- Moisture dynamics in sealed and insulated attics are different than those in vented attics. For example, peak attic air relative humidity is roughly coincident with peak solar irradiance in sealed and insulated attics, whereas vented attics experience the lowest air relative humidity at this time, due to elevated air temperatures.
- Based on long-term averages, house volumes and sealed and insulated attic volumes have similar moisture conditions.
- Many in the field now consider at least partial direct conditioning of the sealed and insulated attic to be crucial, but this may already be provided by air leakage from the duct system.
- When using fibrous insulation, cellulose may provide some beneficial moisture protection, because: (1) it provides moisture storage and acts as a buffer, (2) it reduces air movement in the assembly, and (3) it contains borate preservatives.
- There is limited evidence that humidity levels are somewhat elevated in sealed and insulated attic homes, because the attic serves as a moisture source for the house. During humid periods, the attic stores rather than vents moisture, and this moisture is then released back to the conditioned volume when the driving forces reverse.
- Condensation on the exterior roof surface is an unlikely moisture source for sealed and insulated attic assemblies.
- Elevated indoor humidity in new, energy efficient homes may increase the moisture risk posed by sealed and insulated attics. This problem is greatest in assemblies that do not control condensing surface temperatures through use of exterior insulation or air impermeable cavity insulation.

8.3 Moisture Simulation in Sealed and Insulated Attics

In general, simulation studies have assessed moisture risk due to vapor diffusion through the assembly, which focuses on the tendency for warm, moist air from the occupied space to come into contact with the sealed and insulated assembly. This moist air then promotes vapor diffusion into the assembly (assuming a vapor pressure drive from the attic to outside), or moisture transport by air movement in air permeable assemblies.

Risk in these assessments is determined by the time-varying sheathing moisture contents, with importance placed on the absolute moisture level, as well as the duration of high humidity and seasonal dynamics. Risky assemblies are those that are predicted to have higher moisture contents for longer continuous periods of time. Acceptable criteria are established in ASHRAE Standard 160 (discussed in detail in Section 8.6). Moisture risk by air movement and condensation has typically been assessed by comparing the surface temperature of the roof sheathing (or first condensing surface) with the dew point temperature of the attic air.

Risk is also associated with the assembly's resilience, or its ability to manage unintended moisture intrusion, from either condensation or rain intrusion. Typically, assemblies with low permeance (e.g., ccSPF) perform very well from a vapor diffusion perspective, but can sometimes suffer when unintended moisture intrusion occurs. Nevertheless, some researchers advocate for use of ccSPF roofs across the U.S. in nearly all situations (Schumacher, 2007).

Numerous studies have used hygrothermal simulations to predict accumulation of moisture in sealed and insulated attic/roof assemblies (Lstiburek & Schumacher, 2011; Pallin et al., 2013; Prahl & Shaffer, 2014; Salonvaara et al., 2013; Straube, Smegal, & Smith, 2010). Some of these studies have addressed a variety of assembly types across all U.S. climate zones, such as Straube, Smegal, & Smith (2010) and Pallin et al. (2013). Pallin et al. (2013) performed a parametric study and found that factors most affecting moisture risk in sealed and insulated attics were insulation air/vapor permeance (i.e., open/closed cell spray foam), climate zone, and indoor moisture gains (in descending order of importance), followed by the more marginal impacts of duct leakage, ceiling interface leakage and thermostat set point. The findings from Straube, Smegal, & Smith (2010) were the primary basis for the current code requirements for sealed and insulated attics in the IRC. Others have focused only on certain insulation types and locations, such as ocSPF in CZ1 to 4, by Salonvaara et al. (2013). While not directly assessing sealed and insulated attics, Lstiburek & Schumacher (2011) assessed vented assemblies throughout California with insulation on both the attic floor and roof slope (high performance ventilated attics). Finally, Prahl & Schaffer (2014) focused on the problem of ccSPF in cold climate applications, with imperfections that allowed airflow through the assembly.

The strength of the simulation approach is that researchers can assess the relative performance of a wide variety of different assemblies, using different insulation types (and combinations of types) to understand how assemblies with different thermal, air and vapor characteristics will perform in locations throughout the U.S. The downside to the simulation approach is the complexity of modeling the physical phenomenon driving moisture and temperature in attics, as well as the absence of ground truth information about assembly durability. The dynamics are nuanced and complex, and moisture failures in sealed and insulated attics are rare, such that the variables selected by researchers are not very likely to capture the real world dynamics truly leading to failure. For example, almost every simulation study referenced above did not dynamically model air exchange between the house, attic and outside. In fact, some assumed no air exchange between the attic and outside. Indoor climate conditions were typically derived from very simplified assumptions based on outside air temperature (e.g., EuroNORM). Furthermore, models are not very adept at simulating construction defects and other imperfections that can lead to failure.

As discussed above, in assessments of moisture risk in building assemblies, the coldest surfaces are those that are most likely to become and stay wet. Consistent with this, increased moisture accumulation in sealed and insulated roofs is associated with the nighttime, heating season, colder climate zones, north-facing roof slopes and cool roof surfaces. Another outcome is that while many assemblies appear to have good performance under vapor diffusion conditions, they suffer high moisture levels when liquid water is introduced, whether by condensation induced by exfiltrating air, or by liquid rainwater intrusion. The resilience of these assemblies to imperfections is crucial to their ability to both limit wetting and allow drying. Often those assemblies with higher resistance to vapor diffusion (low permeance) appear to maintain lower sheathing MC, but they respond poorly to moisture intrusion (i.e., wetting more quickly and drying more slowly). For example, Salonvaara et al. (2013) simulated a sealed and insulated attic assembly with ocSPF (23 perms) plus an extra layer of intumescent paint (1 perm). Under diffusion conditions, this assembly had low sheathing MC (<10%), but once wetting by rain intrusion was added, the MC quickly exceeded 20-26%. Grin, Smegal, & Lstiburek (2013) assessed rain water intrusion in sealed and insulated attics directly, and they found that ocSPF could dry more readily than ccSPF after rain intrusion, and that assemblies were able to withstand from 0.6 to 1.5% of annual rainfall intrusion, depending on climate zone and SPF type. ocSPF dried more readily, but also allowed more wetting from diffusion during winter months, so a Class II vapor retarder is required in some climates (per model codes, see Section 4.2).

8.4 Moisture Measurements in Sealed and Insulated Attics

While extremely useful in assessing a wide variety of options for sealed and insulated attics, simulations are limited in their ability to predict reality in the real world. Simulations suggest that many of the sealed and insulated attic assemblies that have been built in the U.S. face substantial moisture risk, yet thousands of such assemblies have been constructed across the U.S. without reports of widespread failure. So, either simulations are not capturing the dynamics that lead to failure, or the metrics used for assessing the outputs of simulations are overly strict or conservative. For these reasons, it is useful to look to field measurements in real homes, which implicitly capture more of the complex dynamics potentially leading to moisture accumulation and damage in attics. Field results are summarized below in Table 8. For example, real-world measurements have made it clear that the peak of the roof is the most common place to see material damage from moisture[16], yet

[16] It is not entirely clear why moisture problems manifest at roof peaks. It could be due to the buoyancy of moist air, such that attic volumes become stratified, with

none of the simulations are able to predict or model this phenomenon (Ueno & Lstiburek, 2015). Field measurements have also confirmed that northern exposed roofs have the highest sheathing MC (Rose, 1992). Field measurements in a roof/attic test facility clearly demonstrated the role that air movement can play, where fiberglass batts with taped and untaped kraft paper facing experienced very different sheathing MC during winter (Rose, 1995). They determined that provision of an air chute between the insulation and roof sheathing protected against high MC, whether the assembly was vented or sealed and insulated.

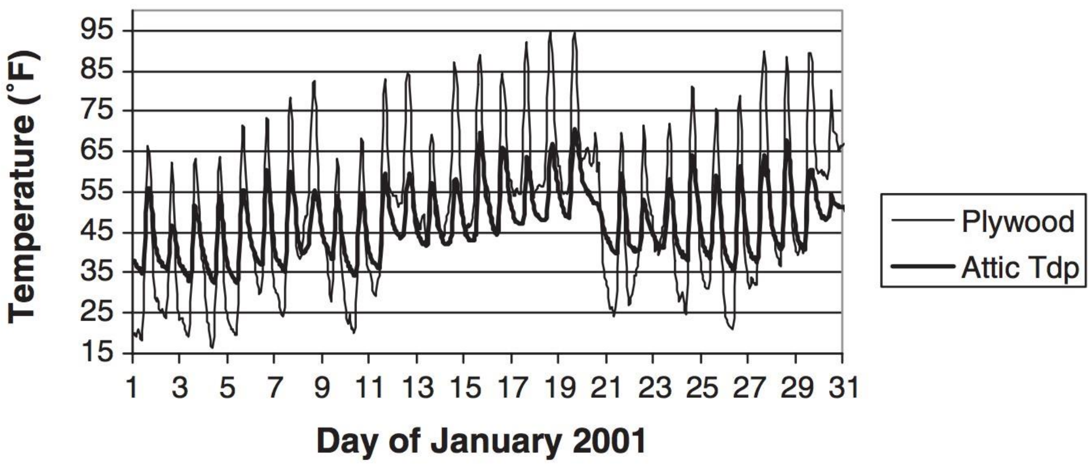

Figure 14 Time series plot of roof sheathing temperature (North-facing) and attic air volume dew point temperature in a Jacksonville, FL . *Source: Rudd (2005)*.

Field research has included monitoring over short- and long-term periods of thermal and moisture conditions in sealed and insulated attic assemblies (Boudreaux et al., 2013; Grin, Smegal, & Lstiburek, 2013; W. A. Miller, Desjarlais, & LaFrance, 2013; W. Miller, Biswas, Kehrer, Desjarlais, & Atherton, 2013; Rose, 1992, 1995; Rudd, 2005; Ueno & Lstiburek, 2015). A chronological summary and discussion of interesting findings in this literature is provided below.

Some of the earliest research measurements of sealed and insulated attic assemblies comes from the Building Research Laboratory at the University of Illinois, where measurements were made in vented (Rose, 1992) and sealed and insulated/cathedralized attics (Rose, 1995). Then using research results from the mid- to late-1990s, Rudd (2005) presented an assemblage of findings from sealed and insulated roof research projects across the U.S. This summary included

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moisture content of air increasing with height. It might also be due to the presence of framing at the roof peak, which might be colder in temperature or might represent locations of air leakage.

deconstructive testing of eight sealed and insulated attic homes insulated with ocSPF—six in cold climates and two in hot-humid climate. Also included, were monitoring assessments in a Houston, TX home with two sealed and insulated attics (R-22 netted cellulose and R-30 unfaced fiberglass batts), as well as a Jacksonville, FL comparison of a vented attic home with a sealed and insulated attic home. Attic moisture measurements in the Jacksonville, FL home are pictured in Figure 14. Finally, a new surge of research was performed in the past three years. Boudreaux et al. (2013) monitored moisture levels in eight homes for a full year, and provided a detailed discussion of moisture dynamics in a single deep retrofit home with sealed and insulated attic in Eastern Tennessee. Grin, Smegal, & Lstiburek (2013) reported on deconstructive assessments of 11 in-service sealed and insulated roof systems across North America, and in all locations the roofs were well within the safe range for wood sheathing. One full-roof failure was reviewed, and it was determined that SPF was installed on wet OSB. Miller, Desjarlais, & LaFrance (2013) reported on field-testing in side-by-side sealed and insulated (ocSPF) and vented attics in Charleston, SC. Most recently, Ueno & Lstiburek (2015) compared performance of a variety of sealed and insulated assemblies under high indoor moisture conditions in a multi-bay comparative roof test facility located in a cold climate, and they also performed long-term monitoring of a single, unoccupied test home in a hot-humid climate.

Based on long-term averages, house volumes and sealed and insulated attic volumes have roughly similar moisture conditions (Boudreaux et al., 2013), though in humid climates some sustained vapor drive from the attic to the house can occur during cooling periods (see Figure 15). Boudreaux et al (2013) also provide data suggesting that house and attic volumes may be more humid in sealed and insulated attic homes, though the authors acknowledge this is the result of an array of differences between the homes, such as moisture gains, set points, cooling demand, etc. This is corroborated by blog comments from practitioners in coastal North Carolina who claim that sealed and insulated attics they construct (and monitor, as a matter of course) are commonly more humid than the house, in terms of relative humidity (Bailes, 2014).

Moisture in attic air and building materials varying dramatically diurnally and seasonally. Attic air humidity can vary widely throughout the day, with excursions near saturation common during summer in hot-humid locations (see peaks in Figure 16) (W. A. Miller et al., 2013; W. Miller et al., 2013; Rudd, 2005). This results from low attic air temperatures (near house temperature), coupled with strong solar driven moisture coming from the sealed and insulated roof assembly. The MC of materials in sealed and insulated roof systems can vary widely on a seasonal basis. For example, Grin et al. (2013) report swings between 4 and 25% in an ocSPF sealed and insulated roof.

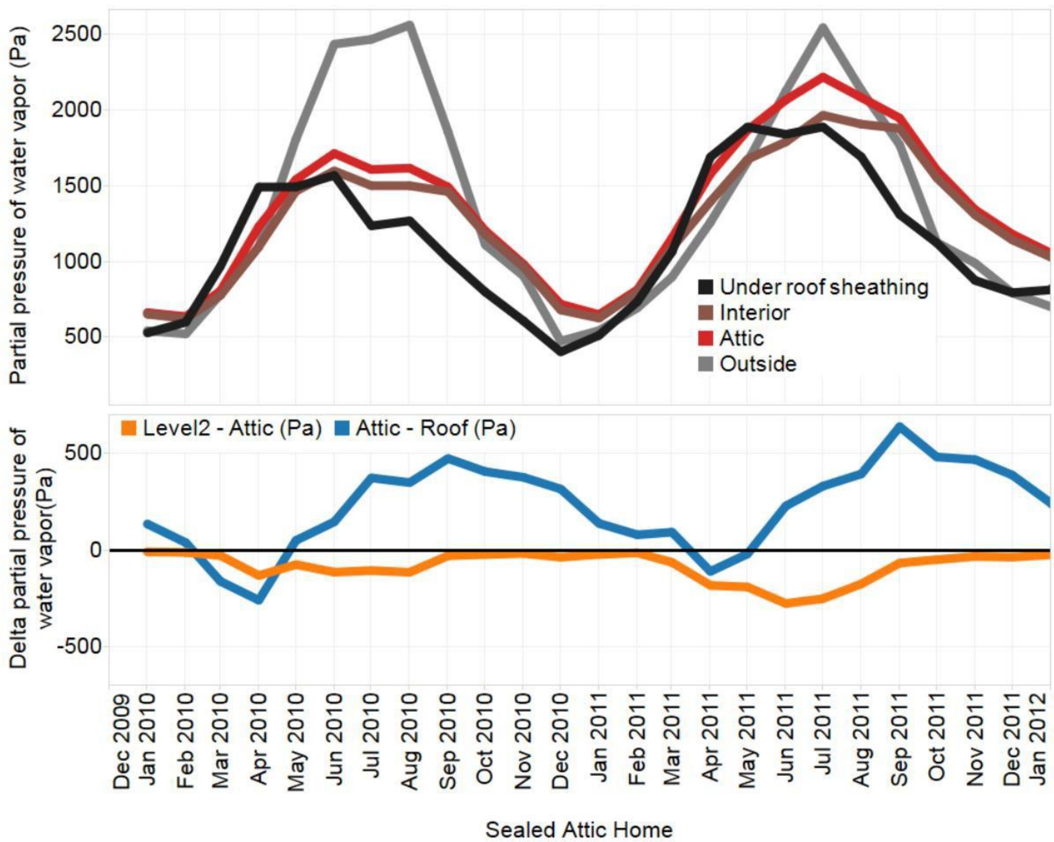

Figure 15 Monthly average partial pressures of water vapor in measurement locations in a sealed and insulated attic in a mixed humid climate. ***Source: Boudreaux et al. (2013).***

When using fibrous insulation (cellulose or fiberglass), cellulose may provide some beneficial moisture protection, because: (1) it provides moisture storage and acts as a buffer, (2) it reduces air movement in the assembly, and (3) it contains borate preservatives, which might help preserve wood it is in contact with. Ueno & Lstiburek (2015) measured annual moisture conditions in seven test roofs in Chicago, IL with fibrous insulation, and upon deconstruction, test bays with fiberglass had substantially greater material damage (see Figure 17). Similarly, Rudd (2005) reported on measurements in a Houston, TX test home with an sealed and insulated attic, with zones using cellulose and fiber glass, and they found that the cellulose dramatically reduced daily peaks in attic air humidity, which were near saturation with fiberglass and were only 60-70% with cellulose. Rudd (2005) also reported that during the winter, both fiberglass and cellulose roofs experienced condensation conditions near the roof peak. Consistent with this, test wall bays insulated by either fiber glass batts, or blown in cellulose or fiberglass, all experienced biological growth and material damage when unprotected by vapor diffusion barriers (Rose & McCaa, 1998).

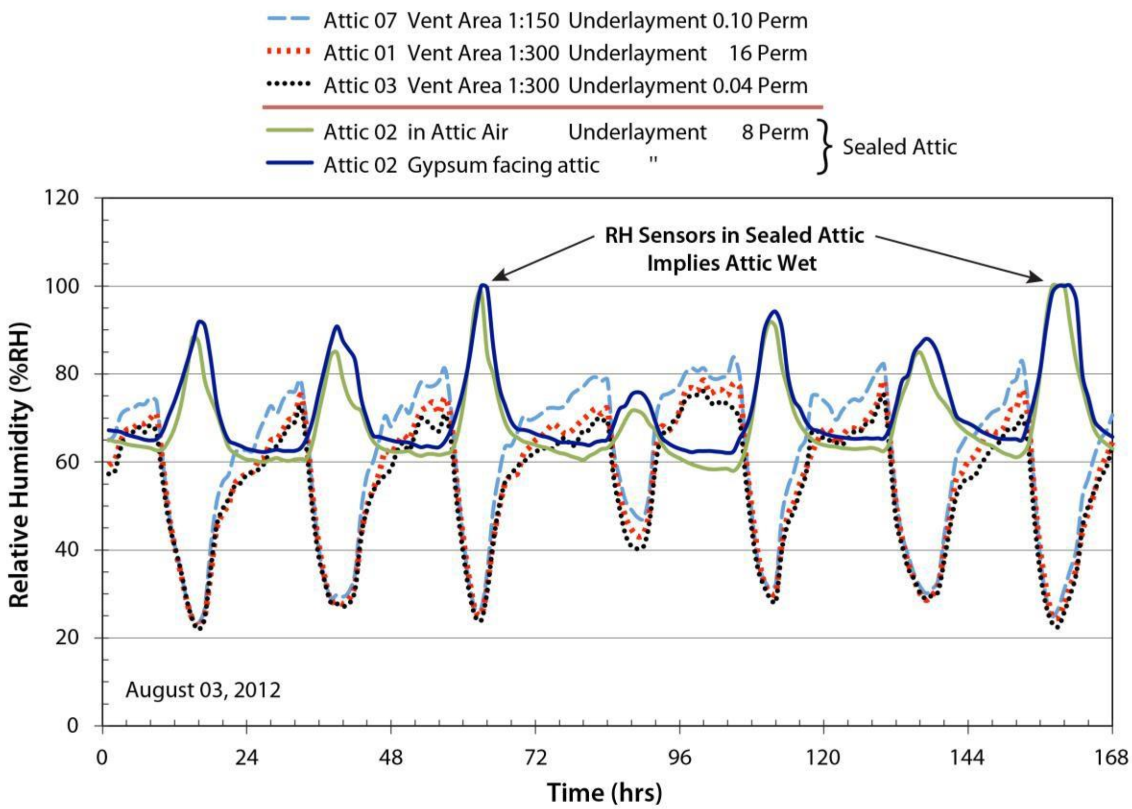

Figure 16 Time series plot of relative humidity in attic air volumes in a series of test roofs at the Natural Exposure Test (NET) facility, located in Charleston, SC. ***Source: Railkar, Chich, Shiaio, Desjarlais, & Miller, 2015.***

Problematic moisture areas tend to be concentrated at the roof peak, a phenomenon that is particularly the case for observed moisture damage and biological growth. For example, in deconstructive testing of a test roof facility in Chicago, IL, Ueno & Lstiburek (2015) found moisture damage to roof sheathing concentrated at the roof peak. Ueno & Lstiburek (2015) also describe earlier experience in Houston, TX, Jacksonville, FL, and in Northern California (see image in Figure 18), where cellulose sealed and insulated roofs were found to have unacceptable condensation and moisture damage at the roof peak. Removal of insulation at the peak eliminated the issue. Similarly, Rudd (2005) reported on condensation and material damage concentrated at the roof peak in hot-humid and cold climate homes with sealed and insulated attics. This is corroborated by hygrothermal measurements in insulated walls in cold climates, where higher moisture contents and material damage were consistently found at the top of wall cavities in a comparative test facility (Rose & McCaa, 1998). Though Forest and Walker (1990) found that bottom plates were in fact the location in walls with the highest MC in Canadian prairie region homes (Tom W. Forest & Walker, 1990).

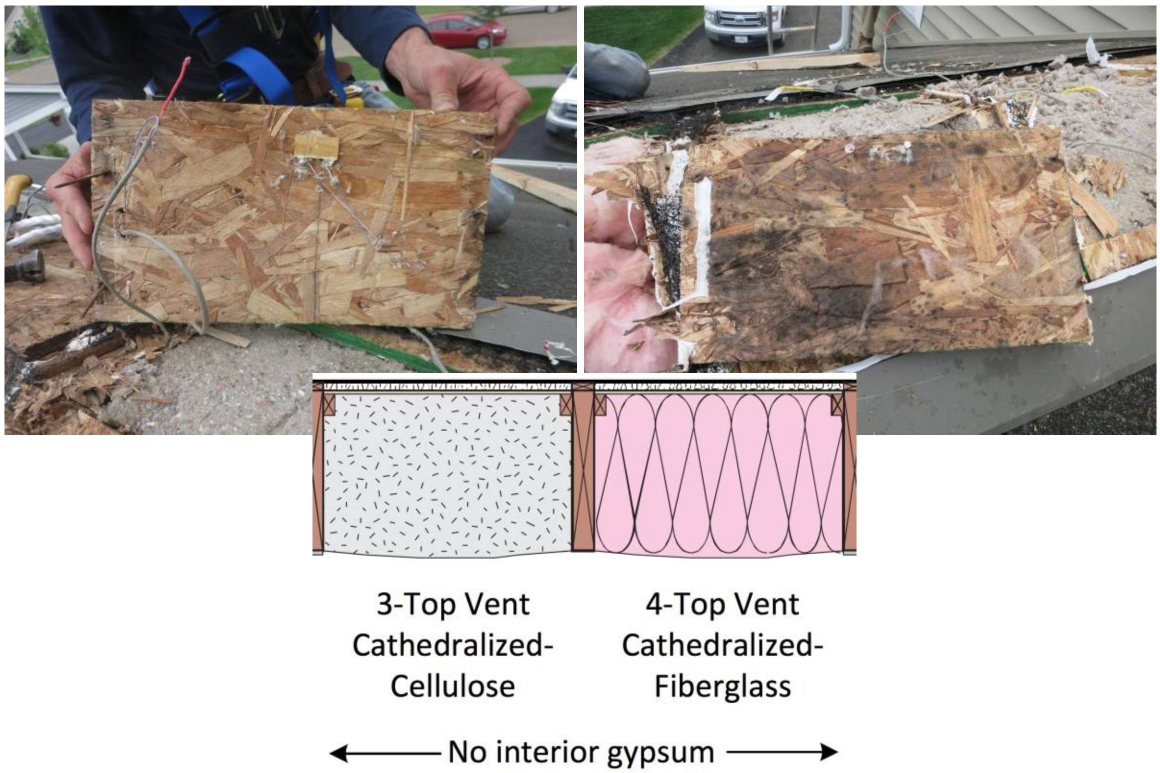

Figure 17 Images showing results of deconstructive assessments of sealed and insulated attic assemblies in a test roof in a cold climate after one year of stress testing (high indoor moisture gains at 50% RH, intended to lead to failure). ***Source: Ueno & Lstiburek, 2015/Building Science Corporation***

Possible causes for this increased risk at the roof peak include: (1) lower effective R-value at the ridge due to geometry effects, (2) increased presence of air leakage pathways or thermal bridges, (3) increased night sky radiative losses at peak or (4) greater buoyancy of moist air mixtures leading to stratification of attic air moisture. These are listed in order of reducing likelihood. The contributions (if any) of these causes have not been clearly demonstrated.

Figure 18 Photographs of deconstruction of a sealed and insulated attic assembly with dense pack cellulose on a home in Northern California that had experienced water dripping at the roof ridge

When research into sealed and insulated attics and moisture began approximately 20 years ago, one proposed source of attic moisture was condensed water that accumulated on roof shingles during cold nighttime hours, later to be driven into the assembly by incident solar energy (Rudd, 2005). Later research has shown that this is an unlikely source of moisture in attics. Boudreaux, Pallin, & Jackson (2013) provided a theoretical building physics-based discussion of the issue, and determined that bulk moisture storage in overlapped shingle roofs was extremely unlikely. Other field research with roof underlayments with varying levels of vapor permeability showed that sheathing moisture content in vented attics was not appreciably affected by the permeance of the roof underlayment (Railkar et al., 2015). Finally, Ueno & Lstiburek (2015) directly tested the presence of solar driven moisture from exterior roof finish, by installing a vapor and air impermeable box attached to the underside of a sealed and insulated attic assembly. They found no evidence of solar driven moisture from the exterior (Ueno & Lstiburek, 2015).

Reference	***Climate Zone***	***Comments/Findings***
Rose (1995)	Cold	Highest sheathing MC is in the sealed and insulated, stuffed condition with untaped kraft paper, with MC consistently exceeding 30%
Rudd (2005)	Hot-Dry	Daily RH in home swung between 28 and 35%, 26 and 40% in the attic, and 24 and 45% at the insulation/sheathing interface
	Cold	North-facing sheathing highest MC. Unacceptably high sheathing MC in 3 of 4 homes; no signs of wood deterioration or biological growth
	Hot-Humid	Winter: North exposure has most sheathing condensation with fiberglass and cellulose, none for ocSPF; Summer: Elevated wood moisture and rusted fasteners were observed near roof peaks; attic air daily pulses near saturation (especially near the peak), effect heavily buffered by cellulose vs. fiberglass
Boudreaux et al. (2013)	Mixed-Humid	4 sealed and insulated attic homes had higher humidity than 4 vented attic homes; Attributed to seasonal transfer and storage of moisture from house to attic in winter, and from attic to house in summer; Strong diurnal patterns in moisture transport from attic air to sealed and insulated roof assembly (called ping-ponging); No evidence of material degradation and minimal mold potential over 4 years in retrofit sealed and insulated attic home
Grin, Smegal, & Lstiburek (2013)	CZ 2-7	10 of 11 deconstructed sealed and insulated SPF roofs showed acceptable sheathing MC; one failure roof had SPF applied to web roof sheathing
Miller, Desjarlais, & LaFrance (2013)	Mixed-Humid	In the sealed and insulated attic, peak relative humidity consistently reached 80 or 90% and sometimes 100% around solar noon; On very hot days, attic air showed super saturation; suggest that at least partial conditioning through a "leaky duct" is essential
Ueno & Lstiburek (2015)	Cold	7 sealed and insulated test assemblies using fibrous insulation, all experienced wood MC, condensation and RH levels high enough to constitute "failures"; Sealed and insulated fiberglass roof showed evidence of wet sheathing and mold growth, but not structural failure; sealed and insulated cellulose showed lesser damage, with rusted fasteners, staining and sheathing grain raise; Provision of diffusion vents at peak resulted in

		similar winter MC, but much faster drying in Spring.
	Hot-Humid	Sealed and insulated roof peak RH reached 90+% in the first winter, and was in the 60-80% range the second winter; dropped to 40-50% as weather warmed; diffusion vents led to drier winter assemblies, but wetter summer assemblies (still within "safe" range); inward vapor drive experiment showed no net-accumulation of moisture in the assembly and no moisture migration from outside.
Miller et al. (2013)	6 vented (R46) and 1 sealed and insulated (R22) attics in South Carolina test facility with varying roof/attic technologies	In summer, sealed and insulated attic experienced daily peaks in relative humidity at or near saturation, due to moisture driven out of the assembly and the low attic air temperatures. These peaks occurred coincidentally with the lowest attic air RH in the vented attics, due to elevated temperatures. Modifications to attic vent ratios had little effect on moisture or heat flux. Condensation potential on roof sheathing was low in all cases.

Table 8 Summary of observed moisture issues in sealed and insulated attic assemblies.

8.5 Methods to Reduce Moisture Risk

As a result of the many benefits of sealed and insulated attics, this construction technique remains popular despite its potential moisture risks. As with all roofs, eliminating the intrusion of bulk rainwater from the exterior must be the first priority. Once bulk water is managed, primary methods for reducing risk in these assemblies are: (1) control of first condensing surface temperatures and (2) control of indoor humidity levels. Secondary methods for reducing moisture risk include: (1) partial direct conditioning of the attic volume, (2) enhanced mixing of the house and attic volumes, (3) use of vapor diffusion caps at roof peaks/ridges, and (4) roof deck ventilation above the structural sheathing. Each of these approaches will be discussed briefly below.

The primary means of mitigating moisture risk in sealed and insulated attics is through control of condensing surface temperatures in accordance with IRC 2012 requirements (see Section 4.2.1). This is reflected in Lstiburek (2006, 2014), where the author discusses attic ventilation in residences based upon decades of research and field experience (Lstiburek, 2006, 2014). He suggests that from a moisture perspective, sealed and insulated attics fall into two broad categories—those where the temperature of the first condensing surface is controlled, and those where it is not. The first condensing surface is typically the attic-facing side of the structural roof sheathing. The surface temperature is controlled by either installing insulation to the exterior of the surface (e.g., rigid insulation on top of the roof deck), or by installation of air impermeable insulation in the cavity in direct contact with the structural roof sheathing. This new air impermeable insulation becomes the new first condensing surface. Currently the IRC stipulates when, where and how this surface temperature should be controlled (see Section 4.2.1). Nevertheless, for background, the author suggests two criteria for deciding if condensing surface temperature control is required: (1) indoor relative humidity should be <45% during the coldest part of the year, and (2) monthly average ambient temperature should not drop below 45°F. The author suggests that hot-dry climate zones of the U.S. are the only location suitable for sealed and insulated attics without control of condensing surface temperatures.

Condensing surface temperatures must be considered along with indoor moisture conditions, because it is the combined surface temperature and air moisture content that determines moisture condensation and accumulation. From this perspective, acceptable moisture performance can be achieved through either raising the temperature of the first condensing surface, or by reducing the dew point temperature of the air (i.e., reducing relative humidity). Commonly, both strategies are advocated, but the code requirements for sealed and insulated attics are based on raising the temperature of the first condensing surface, because indoor humidity levels are less within the designer's control. Yet, unusually high indoor humidity may pose a risk even to sealed and insulated attics following the IRC requirements.

Unfortunately, high performance homes and homes with ducts in conditioned space have been shown to have higher indoor humidity levels, due to reduced sensible cooling loads (Rudd, Henderson, Bergey, & Shirey, 2013; Rudd, Listiburek, & Ueno, 2005; Rudd & Henderson, Jr., 2007). Additionally, measurements of temperature and humidity in 11 deep energy retrofit homes in Northern California showed that monthly average indoor humidity exceeded 45% in cold months in eight of eleven projects (Less, Fisher, & Walker, 2012). These findings further support the need for control of the first condensing surface temperatures. Indoor moisture levels can be controlled through provision of continuous ventilation, local exhaust ventilation in kitchen and bathrooms, and potentially supplemental dehumidification.

The secondary moisture management strategies listed above are not required by code and may not have proven track records of performance.

Many in the field now consider that at least partial direct conditioning of the sealed and insulated attic is crucial. This opinion is expressed by practitioners in blogs (Bailes, 2014), by the Building Science Corporation (Lstiburek, 2014) [17], and by researchers at ORNL (W. A. Miller et al., 2013). Lstiburek (2014) explains the crucial fact that in the past, ducts in the attic were leakier, and they provided unintentional dehumidification/conditioning and mixing with the house volume. But as ducts have become higher performance, this side-benefit has disappeared. Lstiburek also

[17] Joe Lstiburek recommends supply and return of 50 cfm/1,000ft2 ceiling area, similar to that for conditioned crawlspaces.

highlights the issue of intumescent paint requirements on SPF, which is only allowed if air is not exchanged between house and attic—a rule violated when providing supply and return air. In this case, sheetrock is required as an ignition barrier, or future model codes might allow or require a smoke detector in the HVAC return with an automatic shut-off (see discussion in Section 4.2.2). Comments by practitioners in Bailes (2014) suggest that some practitioners (namely in the humid southeast) directly condition all sealed and insulated attics (thought with supply air ONLY, to avoid fire issues), whereas others recommend monitoring of temperature and relative humidity, and they adjust the system if a problem surfaces. Given the average 8% leakage measured in sealed and insulated attic duct systems (see Section 6.5), we consider that inadvertent direct conditioning is already occurring in most cases, and intentional direct conditioning is likely only necessary in cases of very tight duct systems.

Variations in the level of mixing of the house and attic air volumes may also affect the attic moisture level and may mitigate risk. Salonvaara et al (2013) assessed the impacts of mixing between the house and attic volumes with a fixed attic air exchange rate to outdoors using WUFI-Plus. In the humid climates assessed, the outside air was the primary moisture source for the attic and the indoor volume was actively conditioned, so increased mixing with the house reduced attic air relative humidity. Yet, if the house air is the primary moisture source for the sealed and insulated attic (as it would be in a dry California climate or during winter in a cold climate), we expect that increased mixing will increase the attic moisture levels. Mixing may increase, decrease or not change moisture levels in sealed and insulated attics, and the effects likely depend on the season and location. Enhanced mixing is unlikely a primary strategy for mitigating risk, but it may be beneficial when the house is actively conditioned/dehumidified in humid climates.

Use of vapor diffusion caps at roof ridges and peaks is a relatively new innovation meant to reduce moisture risk in sealed and insulated attics. Diffusion vents were field tested by Ueno & Lstiburek (2015) in both cold and mixed-humid U.S. climates. In roof test cells insulated with cellulose, provision of diffusion vent caps at the roof peak led to similar winter time sheathing moisture contents, but the diffusion cap roof experienced much more rapid drying of the accumulated moisture during the winter-to-spring transition. This period is the time of highest mold growth susceptibility. In the humid climate test home, diffusion vents were reported to provide a greater hygric connection between the sheathing and outdoor conditions, which led to higher peak sheathing RH. The authors suggest some possibility of eliminating ASHRAE 160 failures using this approach.

Finally, provision of roof deck ventilation above the structural sheathing is often considered a supporting solution for removing moisture from sealed and insulated assemblies. This can be achieved through (1) batten arrangements for tile roofing materials, (2) multiple layers of structural sheathing with ventilation air gaps, or (3) through use of breathable mesh materials that provides a gap between the structural sheathing and the weather resistive barrier. Unfortunately, Ueno &

Lstiburek (2015) found no consistent evidence of reduction in sheathing moisture contents from use of breathable mesh materials during cold climate high-moisture stress testing. This may have been due to the limited depth of the mesh material. Miller and Kosny (2008) assessed the thermal benefits of advanced roof strategies, such as enhanced roof deck ventilation, and they found improved performance with larger roof deck ventilation air gaps (between 1 and 4”) oriented up-down the roof slope. The large 4” gap was reported to reduce heat gain during summer and reduce heat loss during winter. This effect could both increase the roof sheathing temperature and support moisture removal by convection.

8.6 Assembly Moisture Failure Criteria

8.6.1 Evolution of ASHRAE Standard 160

The current reference for acceptable moisture conditions in building assemblies is ASHRAE Standard 160-2009 *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE, 2009). Here we describe the evolution of the standard, namely we describe: (1) the original criteria, (2) the elimination of two of these criteria, and (3) the future of the standard, which we anticipate will replace all former criteria with explicit modeling of mold growth index, coupled with a single mold index threshold.

8.6.1.1 2009 Criteria

Standard 160-2009 criteria are adapted from the International Energy Agency Annex 14 (IEA, 1990). The performance criteria in Standard 160 are intended to address surface mold growth, which are the most stringent (i.e., conservative) of moisture design performance criteria. The criteria apply to the temperature and humidity conditions at the surfaces of building materials. As originally written, the standard required the following conditions be met:

1. 30-day running average surface RH<80%, when 30-day running average surface temperature is between 5-40°C;
2. 7-day running average surface RH<98%[18] when the 7-day running average surface temperature is between 5-40°C;
3. 24-hour running average surface RH<100% when the 24-hour running average surface temperature is between 5-40°C.

Less stringent criteria are allowed for surfaces naturally resistant to mold growth or that have been chemically treated to be resistant. TenWolde (2010) notes that ASHRAE 160 contains a typo (TenWolde, 2010). He says that the second threshold listed above is “>98%” in ASHRAE 160, whereas the IEA Annex 14 says “>89%”.

[18] Note the discrepancy between the ASHRAE value of >98% versus the IEA Annex 14 value of >89%. TenWolde (2010) suggests this is a typo, to be corrected in future versions of the Standard.

The surface relative humidity criteria listed in ASHRAE 160 can be translated to estimates of equilibrium wood moisture content based on temperature (°C) and relative humidity using Equation 1. For example, at 20°C and 80% RH, the wood EMC is approximately 16%. And at 20°C and 89% RH, the wood EMC is approximately 20%.

$$EMC(\%) = \frac{1800}{W}\left[\frac{Kh}{1-Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2}\right]$$

h = relative humidity (fraction)
$W = 349 + 1.29*T + 0.0135*T^2$
$K = 0.805 + 0.000736*T - 0.00000273*T^2$
$K_1 = 6.27 - 0.00938*T - 0.000303*T^2$
$K_2 = 1.91 + 0.407*T - 0.000293*T^2$

Equation 1 Calculation of Equilibrium Moisture Content (EMC) for wood protected from contact with liquid water and shaded from sunlight (Richard et al., 2010).

8.6.1.2 Addendum A

Standard 160-2009 was revised by Addendum A in early 2011 (ANSI/ASHRAE, 2011). The revision removed the 2nd and 3rd criteria listed above, and the sole remaining requirement was that in order to minimize mold growth, 30-day running average surface RH should be <80%, when 30-day running average surface temperature is between 5-40°C. The addendum gives the following justification for these changes: (1) the remaining condition is sufficient for determining onset of mold growth, (2) the 2nd criteria was called erroneous[19], and (3) the 3rd condition was labeled as not germane to determining mold growth. The standard also became easier to use. It is not clear how these changes to the standard might affect the results of past assessments of sealed and insulated attics that were used to develop requirements in the model building codes (see IRC requirements in Section 4.2).

8.6.1.3 Future of ASRHAE 160 - Mold Index Modeling

The ASHRAE Standard 160 criteria for time-dependent surface relative humidity and temperature conditions have been critiqued for being too conservative and for not reflecting the actual dynamics of mold growth in building assemblies (Glass, Schumacher, & Ueno, 2015). For example, the relative humidity threshold of 80% is the lowest moisture level where mold growth begins, but this relationship is temperature dependent, such that at colder temperatures, the surface RH required for mold growth is substantially greater than 80% (see Figure 19). The critical surface RH also varies across building materials. The simple approach currently embodied in Standard 160 also does not account for the benefits or risks of cyclic periods of wetting or drying. The conservatism of the standard is purported to lead to "failed" assemblies that have no evidence of degradation, as well as to

[19] See discussion of TenWolde (2010).

unnecessarily strict design criteria, which limits the flexibility of building envelope designs and increases their costs.

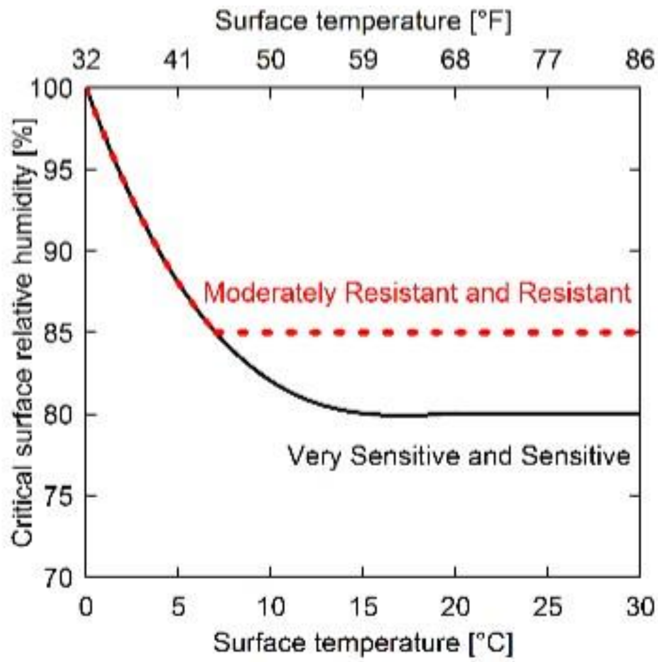

Figure 19 Plot of the temperature dependence in critical surface RH from draft of ASHRAE Standard 160-2009 Addendum E.

Recent research has developed better mold growth models, which incorporate material sensitivity classes, as well as time-varying dynamics of wetting/drying and temperature (Ojanen et al., 2010; H. Viitanen et al., 2010; Hannu Viitanen & Ojanen, 2007). While still not perfect (Vereecken, Vanoirbeek, & Roels, 2015), these models represent the best current tools for assessing moisture risk in hygrothermal simulations. Use of criteria based on the mold index are more likely to capture truly risky assemblies, and less likely to identify safe assemblies as problematic.

In order to address these issues and to align the standard with recent research findings in mold growth processes, the Standard committee is considering a proposed Addendum E. This Addendum removes the single remaining criteria listed above, and it adds a threshold for the mold index, as well as equations for calculating the mold index. Proposed mold index calculations include sensitivity classes for various materials in alignment with their susceptibility to mold growth. Classes include untreated wood, wood panel products, cementitious materials, etc. At the time of this writing, the Standard 160 technical committee has voted to adopt mold index calculations and thresholds, with material sensitivity classes, but the proposed addendum must receive public review comments and final ASHRAE approval prior to formal incorporation into the standard.

8.6.2 Other Criteria

Other criteria for moisture performance assessment are more subjective than Standard 160, such as material degradation or visible mold growth, as are used in deconstructive assembly investigations. In-situ wood moisture content measurements are also used to assess assembly acceptability/performance. A common and simple approach to determining moisture acceptability is based on the dew point temperature of the attic air coupled with prediction of the sheathing surface temperature, which is considered the primary condensing surface in most sealed and insulated attics. Periods of time when the surface temperature is predicted to be below the air dew point temperature are labeled as "risky".

9 Energy Performance of Sealed and Insulated Attics

The energy performance of sealed and insulated attics has been assessed through field measurements in full-scale homes and in attic test facilities, as well as through building and attic simulations. Performance has been assessed in several ways: (1) whole house performance in occupied and unoccupied homes (i.e., HVAC system energy use), (2) assessments of attic or ceiling heat flux, and (3) measurements of HVAC distribution system efficiency.

The energy performance of sealed and insulated attics is highly dependent on other parameters, including the insulation levels provided on the roof surfaces (often less than that provided on vented attic ceilings), the presence of HVAC equipment in the attic, the presence of air leakage in the HVAC distribution system, and the roof construction assembly (solar properties, radiant barrier, etc.).

We draw the following conclusions from the literature:

- Performance is highly dependent on several parameters, including the insulation levels provided on the roof surfaces (often less than that provided on vented attic ceilings); the presence of HVAC equipment in the attic; the presence of air leakage in the HVAC distribution system; and the roof assembly characteristics, such as roof solar absorptance and the presence or absence of a radiant barrier in the attic.
- Insulation levels on sloped roof surfaces above sealed and insulated attics (and on gable walls) should be similar to or greater than insulation levels on the floors of vented attics.
- Energy savings are only expected for sealed and insulated attics if they contain HVAC systems and ducts. Savings increase when ducts are leaky or poorly insulated.
- Very little field data exists on the energy performance of sealed and insulated attics. Short-term field tests suggest that cooling energy savings range from 6 to 20%, and heating savings range from 0 to 25% (depending on wind conditions). The presence of leaky ducts in the attic is the clear determinant

of energy performance. In real-world tests of tight duct systems (i.e., not controlled experiments), very little performance benefit has been reported.

- Limited measurements of HVAC distribution efficiency (using calculation and reporting methods from ASHRAE Standard 152[20]) have been made in sealed and insulated attics. Measurements in modern, new California homes (Title 24 2013) found 6-7% improvements in seasonal heating distribution efficiencies, and 8-11% improvements in seasonal cooling distribution efficiencies. Past measurements in poorly constructed (i.e., leaky and inadequately insulated) sealed and insulated attics found no distribution efficiency benefit relative to vented attics.
- In simulations, sealed and insulated attic performance varied considerably with climate zone, with greater absolute energy savings in climates with higher heating or cooling demand. Annual energy savings are at most 20% and more commonly 3-10%. As was indicated by field measurements, the presence of HVAC ducts in the attic and the level of duct leakage, were consistently found to be very important factors in determining energy savings. Simulations show mixed results for airtight duct systems, with some research reporting meaningful savings. The most recent simulation assessments of new code-compliant California homes predict substantial average savings on the order of 13 to 18%, relative to traditional vented attic, code-compliant cases.
- Peak demand reductions are highly climate variable, and have been reported between 0 and 1 kW.
- Simulations in locations across the U.S. have consistently suggested that combining sealed and insulated attics with white roof coverings provides superior performance, though a heating season penalty will exist in most places. Annual energy cost and source energy savings are still evident, with the possible exception of the coldest locations, such as Minneapolis, where heating penalties and cooling benefits approximately cancel out.

A key issue in the energy performance of sealed and insulated attics is the insulation value of the sealed and insulated roof and the conduction heat transfer through this surface. Sealed and insulated attics tend to have both higher overall heat transfer coefficients (UA-values) and higher temperature differences (ΔT).

Sealed and insulated attics always increase the surface area for heat transfer due to conduction, and as a result, sealed and insulated roofs would need additional thermal resistance to perform equivalently with a vented attic (i.e., for the home to have equal UA values). Unfortunately, common practice has been to insulate sealed

[20] ASHRAE Standard 152 *Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems* provides estimates of the efficiency of thermal distribution systems under heating and cooling operation for use in estimates of energy consumption and/or equipment sizing. Seasonal weather conditions are used for energy estimates and design weather conditions for equipment sizing. Calculations are based on measured parameters and factors including duct location, air leakage and insulation of ductwork.

and insulated roofs to *lower* thermal resistances than their vented attic counterparts. This is due to other perceived benefits of sealed and insulated attics, such as enhanced air sealing and consistent thermal performance, meaning practitioners think they need less thermal resistance. It is also due to the common practice of using of spray polyurethane foam products to create sealed and insulated attics. First, these products are more expensive than fibrous insulation, and they have perceived air-sealing benefits, such that practitioners feel they need less thermal resistance (i.e., R-value). Second, they are limited in their application depth due to curing requirements and fire safety concerns. This "problem" can be solved through application of SPF in multiple layers, but this has been uncommon in actual practice.

In addition to the tendency for vented and sealed and insulated attics to have higher overall heat transfer coefficients (UA's), the boundary conditions at the thermal barrier are also different (i.e., different ΔT). As noted above, the UA tends to be larger in sealed and insulated attics, but the ΔT is also often greater. In a sealed and insulated attic, the roof finish serves as the exterior thermal boundary, and under cooling demand, this surface is almost always hotter than the attic air would be in a vented attic. The surface is also cooler than the attic air at nighttime, due to night sky radiation losses. In combination, this means more heat gain during the day and more loss at night. During winter, the ΔT across the assembly is from the house temperature to the outside air temperature, rather than from the house to the attic air temperature, which is typically buffered between the house and outside (though closer to outside). Once again, the ΔT can be greater.

The HVAC equipment and its distribution system is the other primary driver of energy performance of sealed and insulated attics. Relative to vented attics, sealed and insulated attics with HVAC systems in the attic volume can have better energy performance. The attic volume in sealed and insulated attics is more closely coupled with the house conditions, whereas vented attics are well coupled with outside conditions. In either heating or cooling conditions, this tends to reduce the thermal losses or gains from the HVAC equipment and its distribution system. This effect will be greatest for distribution systems that are poorly air sealed and poorly insulated. The effect is attenuated when good distribution systems are present. In general, thermal losses and gains are reduced, and any losses/gains that do occur can be largely recouped within the thermal envelope.

The solar properties of the roof construction assembly can also have major effects on the performance of sealed and insulated roofs. This is especially important in terms of what base case you compare sealed and insulated attic performance against. For example, sealed and insulated attics have lower attic volume temperatures than conventional vented attics, but use of cool roof surfaces (i.e., with high solar reflectance and low absorbance) can have the same effect, as can use of radiant barriers. Cool roof materials reduce attic temperatures, because more of the incoming solar energy from the sun is rejected rather than absorbed and transmitted to the attic volume. This cooling of the attic volume tends to reduce cooling demand but increase heating demand.

9.1 Measured Energy Performance

Actual measurements of the energy performance of sealed and insulated attics have been rarely reported in the literature, and they have almost exclusively included homes in hot-dry climate regions (Hendron, Anderson, Reeves, & Hancock, 2002; Hendron, Farrar-Nagy, Anderson, Reeves, & Hancock, 2003; Parker et al., 2002; Rudd & Lstiburek, 1996). In general, when measurements have been made, they are for only a very small number of homes, for limited time periods ranging from two days to one month. A summary of the findings of these studies in presented in Table 9. Reported savings have varied widely, and assessments have occurred under different test conditions, but reported cooling energy savings vary from 6 to 20%. The presence of leaky ducts in the attic is the clear determinant of energy performance. In field tests of tight duct systems, very little performance benefit has been reported (see Figure 20 and Figure 21 for tight and leaky ducts, respectively). Reports of measured heating season performance are extremely limited. The only heating energy field performance that we are aware of was performed by Hendron et al. (2003), who performed two days of nighttime testing, under normal and high wind conditions.

Others have reported on tests of HVAC distribution system efficiency, per ASHRAE Standard 152 (Hoeschele et al., 2015; Siegel & Walker, 2003) (also included in Table 9). Siegel & Walker (2003) found very little difference in sealed and insulated and vented attic homes, largely due to poor implementation of the sealed and insulated attic approach (attics were leaky to outside). Distribution system efficiency measurements provided by Hoeschele et al. (2015) provide an important counterpoint to the finding above that sealed and insulated attic homes have not demonstrated savings relative to tight, insulated duct systems in vented attics. Hoeschele et al measured distribution system efficiency in a small sample of modern Title 24 (2013) homes in California, comparing those with ducts in conditioned space (and vented attics) against traditional vented attics homes (with duct leakage to outside of 3-6%). They reported 6-7% improvement in seasonal heating distribution efficiencies, and 8-11% improvements in cooling efficiencies.

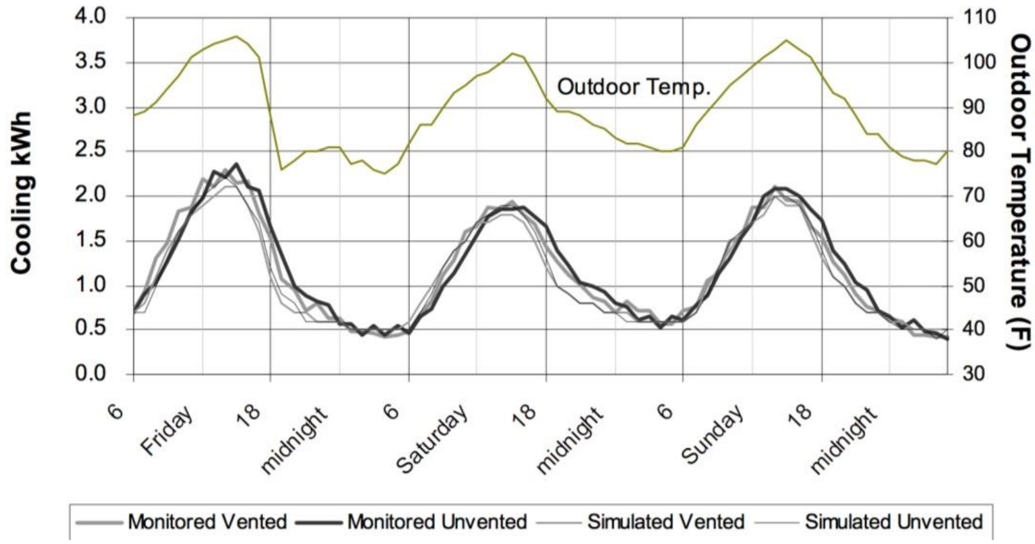

Figure 20 Airtight HVAC ducts. Summer cooling period tests in vented and sealed and insulated attic homes in Las Vegas, NV. Source: Hendron et al. (2002).

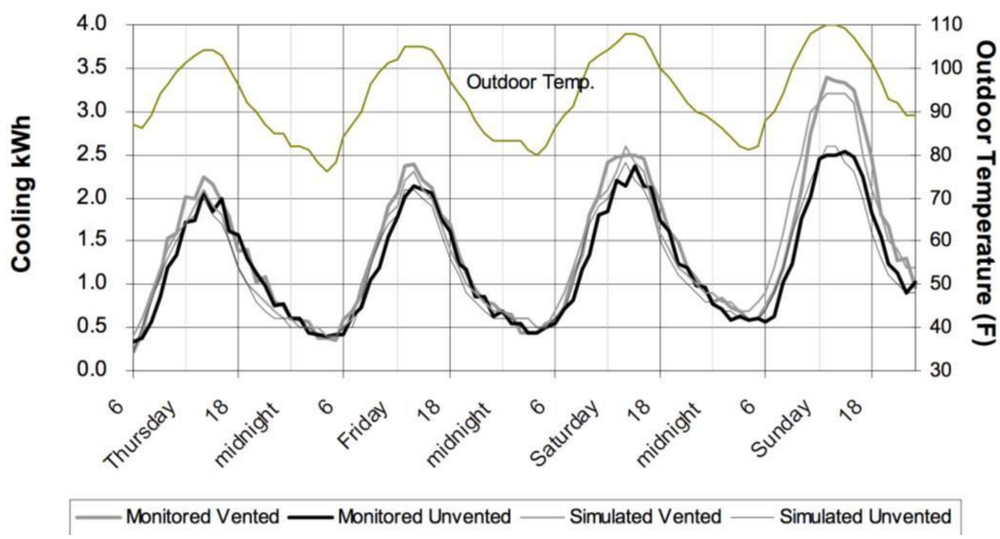

Figure 21 Figure 21 Leaky HVAC ducts. Summer cooling period tests in vented and sealed and insulated attic homes in Las Vegas, NV. Source: Hendron et al. (2002)

Source	***Location***	***House Types***	***Finding***
Hendron et al. (2002; 2003)	Las Vegas, NV	1 sealed and insulated house (R-22 roof) and 1 reference vented attic (R-30 ceiling)	*Cooling:* **Max 20% cooling energy savings** with very leaky ducts. Average savings of 50 to 810 watts depending on duct leakage (from 30 to >100 cfm supply and return leakage); *Winter:* under "normal" wind conditions, same heating energy use (0.012 vs. 0.011 $ft^3/hr\text{-}ft^2$ natural gas); under high wind, sealed and insulated prototype used almost 25% less (0.017 vs. 0.013 $ft^3/hr\text{-}ft^2$ natural gas)
Parker, Sonne & Sherwin (2002)	Fort Meyers, FL	1 sealed and insulated attic house (R-19 roof) and 1 reference vented attic with dark asphalt shingles (R-19 ceiling)	Sealed and insulated attic reduced cooling energy **6-11% (220-400 kWh)** relative to vented roof. Essentially **no savings during peak** 4-6pm period, but peak day savings of 11%.
Rudd & Lstiburek (1996)	Las Vegas, NV	2 sealed and insulated attic homes and 1 reference vented attic (1:150)	Sealed and insulated attic homes had an average of **19% reduced cooling demand** (15 and 22%)
Siegel & Walker (2003)	California	4 sealed and insulated and 5 vented attic homes	HVAC distribution **system efficiency did not differ in vented and sealed and insulated attics** (average of 85% versus 84%).
Hoeschele et al. (2015)	California	5 vented attic homes and 4 vented attic homes with ducts in conditioned space (DCS) + 1 high performance	Cooling delivery efficiency was 4-10% better in advanced attic homes; **6-7% improvement in seasonal heating distribution efficiencies, and 8-11% improvements in cooling seasonal** (ASHRAE 152 seasonal distribution system efficiencies)

		attic (HPVA) (see Section 4.1.3.2)	

Table 9 Summary of findings from measurements of whole house energy performance of sealed and insulated attics in hot climates.

9.2 Simulated Energy Performance

Simulation of the energy performance of sealed and insulated attics is more common in the literature (Desjarlais, Petrie, & Stoval, 2004; GARD Analytics, Inc., 2003a; Hendron et al., 2002, 2003; Hoeschele et al., 2015; W. A. Miller et al., 2013; W. A. Miller & Kosny, 2008; Parker et al., 2002; Roberts & Winkler, 2010; Rudd & Lstiburek, 1996, 1998, 1998; Siegel, Walker, & Sherman, 2000; Wei et al., 2014). Unfortunately the complex physics of attics can make modeling efforts particularly fraught with uncertainty, bias, etc. For example, a number of studies predict increases in energy use with the sealed and insulated attic strategy (Hendron et al., 2002), or increases in heating energy use (GARD Analytics, Inc., 2003a). Also, the results can be sensitive to the insulation levels assumed for flat ceilings versus sloped roof surfaces, which have sometimes been limited to approximately R22, as assessed by DesJarlais Petrie & Stoval (2004). A summary of sealed and insulated attic simulation studies and their results is provided in Table 10. Simulations vary based on tools used, periods assessed (from peak day to annual), inclusion of both heating and cooling energy use, and many other parameters.

Unsurprisingly, sealed and insulated attic performance was reported to vary considerably with climate zone, with greater benefits in climates with higher heating or cooling demand. Annual energy savings are at most 20% and more commonly 3-10%. As was indicated by field measurements, the presence of HVAC ducts and the level of duct leakage were consistently found to be very important factors in determining energy performance. Some simulations suggest that energy benefits disappear when duct leakage is reduced to low levels (<5 or 6%) (GARD Analytics, Inc., 2003a; Hendron et al., 2002, 2003), whereas others indicate that modest but meaningful differences still exist with tight ducts (Hoeschele et al., 2015; Rudd & Lstiburek, 1998; Siegel et al., 2000; Wei et al., 2014). The most recent assessments of new code compliant California homes suggests that substantial average savings of 13 to 18% are expected, relative to typical vented attics, even with low duct leakage. Comparisons of HVAC energy consumption in sealed and insulated attic homes with varying levels of duct leakage suggest that increasing leakage from 4 to 20% can increase annual consumption by 5 to 15% with high climate variability (Pallin et al., 2013). Simulations have consistently suggested that combining sealed and insulated attics with white roof coverings provides superior performance (Desjarlais et al., 2004; Rudd & Lstiburek, 1998). It is clear that performance trade-offs exist between cooling and heating season energy performance. For example, use of white roof surfaces have strong cooling benefits, but are generally associated with heating energy penalties, though annual net-benefits are still evident in most climates. In order to consistently provide net-energy benefits, sealed and insulated attics should be at least as well insulated as conventional attic ceilings.

Source	***Simulation***	***Description***	***Finding***
DesJarlais, Petrie & Stoval (2004)	AtticSim	Varied climate zones, attic/ceiling insulation, and duct system efficiency	Vented attics without ducts outperformed sealed and insulated attics. Sealed and insulated attics had lower annual operating costs than the corresponding vented attics containing ducts. R-22 not sufficient in sealed and insulated designs. Cooling performance strongly dependent on duct leakage; heating benefit for sealed and insulated attics irrespective of duct leakage.
Hendron et al. (2002, 2003)	DOE2.2; no radiant heat transfer between roof deck and attic surfaces	Simulations performed for sealed and insulated attics in hot-dry and other U.S. climates	With duct leakage >5%, sealed and insulated attics produce meaningful savings for cooling (8-20%); highly climate zone dependent. Reported that Annual cooling demand was always higher in the sealed and insulated attic in Sacramento
Siegel, Walker, & Sherman (2000)	REGCAP	Sealed and insulated attic simulation on design day in Sacramento, CA with varying system efficiency specs	Sealed and insulated attic benefits greater as duct efficiency worsened; sealed and insulated attics less sensitive to system performance issues. Sealed and insulated attics had faster pull-down times by 1 to 2.5 hours. Sealed and insulated cases all used less energy than their vented attic matched-counterparts. 40-50% cooling energy savings in sealed and insulated attics relative to 22% duct leakage vented attic.
Roberts & Winkler (2010)	BEopt	Sealed and insulated attic with code typical insulation levels in hot climates	14-17% annual cooling savings from moving ducts inside the house in hot climates, approximately 20% reductions in peak demand (0.75 kW) and

			required system sizing (0.5 to 1 tons).
Rudd & Lstiburek (1998)	FSEC 3.0	Varied insulation in vented and sealed and insulated assemblies with an without duct leakage in Orlando, FL and Las Vegas, NV	Annual simulations in Orlando and Las Vegas showed 2% and 4% annual savings with no duct leakage, and 16% and 10% annual savings with typical duct leakage. Sealed and insulated attic with white roof and no duct leakage saved 12% and 5%.
Miller, DesJarlais, & LaFrance (2013)	AtticSim II		For existing homes, they estimate savings of 28% in Austin (R30 vented attic with 20% duct leakage) and 50% savings with 10% duct leakage. In Baltimore, savings of 26 and 43% are estimated, for sealed and insulated attics with 20 and 10% leakage. In Minneapolis savings are 23 to 41%.
GARD Analytics Inc. (2003)	DOE2.1E	Baseline vented attics with 6 and 22% duct leakage and cathedralized attics, three representative homes in CA climates.	On average, 1- and 2- story homes save 2,000 and 3,400 kWh per year. Savings are 3x the average in most severe CA climates. Total electricity savings varied from 7 to 18% with high leakage, and were only 3-7% with tight ducts. Heating energy use increased in almost all cases and climates from 0 to 24%. With tight ducts, cooling savings were reduced, and heating penalties were increased, such that the net-benefit was reduced or eliminated. Energy cost savings still predicted in all climate zones, even with tight ducts (avg. $138 and $198 in 1- and 2-story homes with 6% leakage).
Wei et al. (2014)	CBECC Res V.650	Baseline vented attic conforming to CA Title 24	Predict average 13% (2-17%) time dependent valuation (TDV) energy savings. Highly

		2013 vs. vented attics with insulated roof decks and/or ducts entirely in conditioned space	climate dependent. Weighted average annual savings of 229 kWh, 18.3 therms and 0.4 kW demand reduction. *Ducts in conditioned space* savings varied from 0-976 kWh, 2-92 therms and 0-1 kW demand reduction. *R-13 roof deck and insulated attic floors* savings were less, 11-688 kWh, 3-56 therms and 0-0.7 kW demand reduction.
Hoeschele et al. (2015)	CBECC-Res compliance model (version 3b1, current as of January 31, 2015)	Baseline Title 24 (2013) compliant vented attic home, compared with ducts in conditioned space options.	Statewide weighted average heating savings of 17% (28.6 therms); cooling savings of 18% (187 kWh); average peak demand reduction typically >20% (0.36 kW, from 0 to 1 kW). Results highly sensitive to insulation and envelope leakage levels.

Table 10 Summary of simulation studies of the energy performance of sealed and insulated attics.

9.3 Comparison of Performance with Other Advanced Roofing Options

While sealed and insulated attics have been used in high performance homes for the past two decades, other advanced roofing strategies (including vented and sealed and insulated attics) have emerged more recently. These advanced strategies combine cool roofing materials, radiant barriers, back-vented roof cladding, roof deck insulation, phase change materials and others. These approaches are intended to reduce the extreme temperatures typical in conventional attics, and to make the attic air similar in temperature to outside ambient air. Simulations of advanced roof options suggest that their energy performance can be similar to sealed and insulated attic approaches.

Such advanced roof options are embodied in the Prescriptive Package-A, Options A, B and C in the 2016 California Title 24 energy codes (described in detail in Section 4.1.3.2). Research in support of these prescriptive code options includes simulations by Wei et al (2014) and measurements of duct system distribution efficiency by Hoeschele et al (2015). Wei et al simulated the packages representing advanced attics in the Title 24 energy code, and they found that electricity and gas savings were predicted in all climates (highly variable), with more savings in the ducts in conditioned space approach. Wei et al also compared the DCS strategy to a traditional sealed and insulated attic with insulated roof deck, and they found that the DCS strategy slightly outperformed the sealed and insulated attic. They cite the following reasons: (1) no whole house fan was simulated for the sealed and insulated attic, (2) the sealed and insulated attic had no radiant barrier installed and (3) a higher temperature difference exists across the insulated roof deck than across an insulated attic floor. While not discussed, it seems likely that sealed and insulated attic performance was equivalent to or better than the insulated roof deck (HPVA) approaches. Performance for the sealed and insulated attic improved as insulation at the roof deck was increased from R-19 to R-38. They illustrate energy use increases in many California climates when using only R-19 at the roof deck (CZ 5-10 and 12), which is in agreement with some past modeling studies that predicted energy use increases in sealed and insulated attics that are insulated to R-20 (see Section 9.2).

Research into advanced roof options outside of California have been reported by Miller and Kosny (2008), who performed simulations and field measurements of different test configurations on the Envelope Systems Research Apparatus (ESRA) roof test system. They describe dramatic reductions in roof assembly heat flux from cool roof finishes, with different approaches to back ventilation via battens or high-profile tiles, with reductions varying between 20 and 90% in heat flux relative to dark shingle roofs. Larger venting spaces worked better, as did radiant barriers and incorporation of phase change materials. The best performing assemblies had peak attic air temperatures that never exceeded the outdoor ambient, compared with a peak of 120°F (48.9°C) in the reference dark shingle roof. They used AtticSim II to simulate different air gaps (1-4") in advanced roof deck assemblies in a code compliant house (2005 Title 24) in Sacramento, CA (see discussion of air gap modeling issues in Section 3.4). The airspace above the sheathing led to reduced heat loss during winter and reduced gain during summer (for both ducts and attic assemblies), thus removing the typical heating energy penalty associated with cool roofs. California homes with 4" air gap assemblies in Sacramento, El Centro and Burbank had annual reductions in ceiling and duct heat transfer of 12, 18 and 19%, respectively. These savings doubled or tripled when ducts were placed in conditioned space.

More recent field assessments have assessed the effects of attic ventilation, radiant barriers, above sheathing ventilation and use of vapor (im)permeable roofing underlayment (W. Miller et al., 2013). They compared numerous configurations of vented roofs with R-46 ceiling insulation against an R-22 sealed and insulated attic with ocSPF. The sealed and insulated attic had reduced winter heat flux by 124% and summer flux by 79%. Ceiling winter heat transfer was 69% greater than in the base case. Not surprisingly, the sealed and insulated attic had the highest heat gains and losses across the ceiling, due to the reduced thermal resistance (R-22 vs. R-46). Authors suggested the primary value of sealed and insulated attics is to reduce losses from leaky ducts.

Others have reported on retrofit re-roofing technologies using roof-integrated PV laminates, dense fiberglass insulation with reflective foil facing and phase change materials (Biswas, Miller, Childs, Kosny, & Kriner, 2011). Test roof data showed reductions in attic-generated heating and cooling loads of 30 and 40%, respectively. Similarly, the use of fibrous insulation materials impregnated with phase change materials has been shown to provide load reductions of 25-35% during peak hours, and may provide passive cooling equivalent to 25% of the daily cooling load (Kośny, Fallahi, Shukla, Kossecka, & Ahbari, 2014).

These advanced roof approaches all likely provide some reduction in moisture risk relative to a sealed and insulated attic. They allow moisture in the attic to vent to outside, and they also have lower levels of roof deck insulation, which might reduce the risk of moist inside air coming into contact with cold roof sheathing.

10 Discussion of Sealed and Insulated Attics in New California Homes

Ultimately, the goal of this project is to research and assess the value and risks of the sealed and insulated attic approach in new California homes. More specifically, the project is considering creation of sealed and insulated attics using only air permeable, fibrous insulation. This approach is being considered in the context of the advanced attic options that now form the prescriptive compliance pathways in California's 2016 Title 24 energy code (see Section 4.1.3.2). Lower-cost sealed and insulated attics that are moisture-safe offer another strong option for designers and contractors who are seeking flexibility in complying with the state's energy code.

General market barriers to placing ducts in conditioned space have already been discussed in the California context (GARD Analytics, Inc., 2003b; Wei et al., 2014). The approach being investigated in this research addresses other concerns, namely: (1) the high cost of SPF insulation, and (2) the lower effective insulation values often achieved in SPF and other fibrous insulation solutions for sealed and insulated attics.

The literature has shown that with minimal insulation on a sealed and insulated attic (i.e., ~R-20), energy savings can be limited, or energy use can even increase. In the past, typical approaches to sealed and insulated attics in California have included the use of SPF insulation, as well as the use of draped netting that is stapled to the upper roof truss chords and then blown with fibrous insulation (see example in Figure 22). Both approaches commonly suffer from low assembly R-values. The netted and blown approach commonly has insufficient effective insulation value, due to uninsulated truss chords and compacted insulation in each cavity. Alternatively, some contractors will install additional framing to make the rafter cavity deep enough to fully incorporate the required insulation depth, but these systems still suffer from thermal bridging at the framing. Use of SPF insulation can unfortunately lead to both higher costs and poorer thermal performance, if adequate insulation depth is not installed. Not surprisingly, high material costs and limited installation depth are the key reasons why SPF is commonly installed to only minimum R-values (i.e., ~R-20)[21].

Higher R-value sealed and insulated assemblies are needed that are lower in cost. Non-SPF commercial products are needed that can achieve installed R-values that comply with Title 24 requirements. One commercial product for sealed and insulated attic assemblies using only fibrous insulation is the Owens Corning ProPink, which has over 25 installations in California (Carpino, 2014). Installations in Northern California have included a vapor retarder, which is required per the product data sheet in CEC climates 1, 2, 3, 11, 12 and 16 (Owens Corning, 2015). The product is currently approved for use in IECC climate zones 2B and 3B. Other approaches include the use of pinned-in-place fiberglass batts, typically applied in two alternating layers.

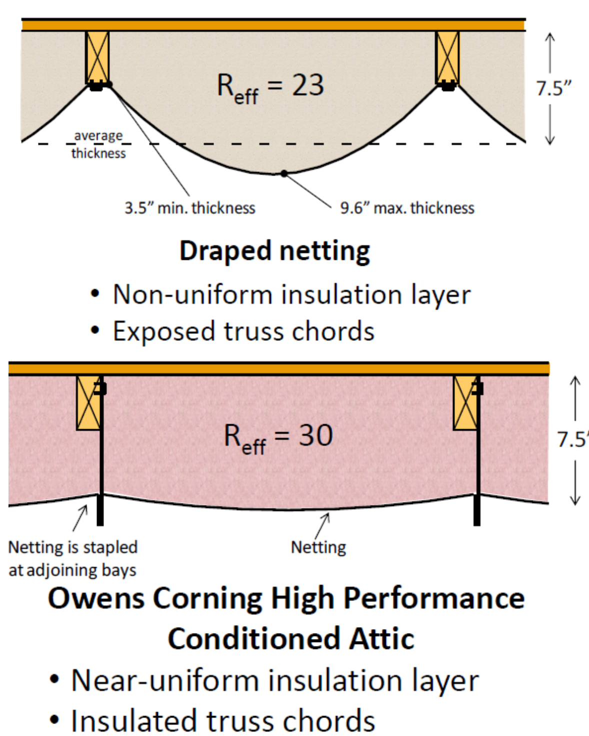

Figure 22 Image from Carpino (2014) comparing standard netted insulation approach with full-depth Owens Corning Approach

Some key questions for these approaches in the California context are:

- What energy savings do we expect from sealed and insulated attics in new California homes built to Title 24 2013/2016?
- What are the moisture-related risks of sealed and insulated attics constructed with entirely air permeable insulation?

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[21] As noted elsewhere, the perception that SPF insulation "works" better also contributes to its use in this application, largely because of its ability to act as an air barrier.

- How might a builder/designer choose amongst the advanced attic/roof options in the 2016 building energy code?

10.1 California Climate Zones

California climate zones are highly variable, with IECC climate zones in the state that include 2B, 3B, 3C, 4B, 4C, 5B, 5C and 6B (see Figure 23). In Building America climate zone terms, these include hot-dry, mixed-dry, marine, and cold climates (Baechler et al., 2010). The amount of new home construction that is occurring in the different CA climate zones is also highly variable. For example, most new development in the state is occurring in climate zone 3B, in the Central Valley and Inland Empire regions of Southern California (see Figure 24). Nevertheless, for code purposes, sealed and insulated attic strategies should be developed that can work anywhere in the state. Furthermore, these climates pose different risks, in terms of the moisture performance of sealed and insulated attics. Marine climates tend to have higher outdoor humidity, which can contribute to elevated indoor humidity and increased risk. Cold climates have the most likelihood of long-term cold roof sheathing temperatures, and the associated risk of condensation. The hot-dry locations have semi-cold winters and strong night sky radiative cooling.

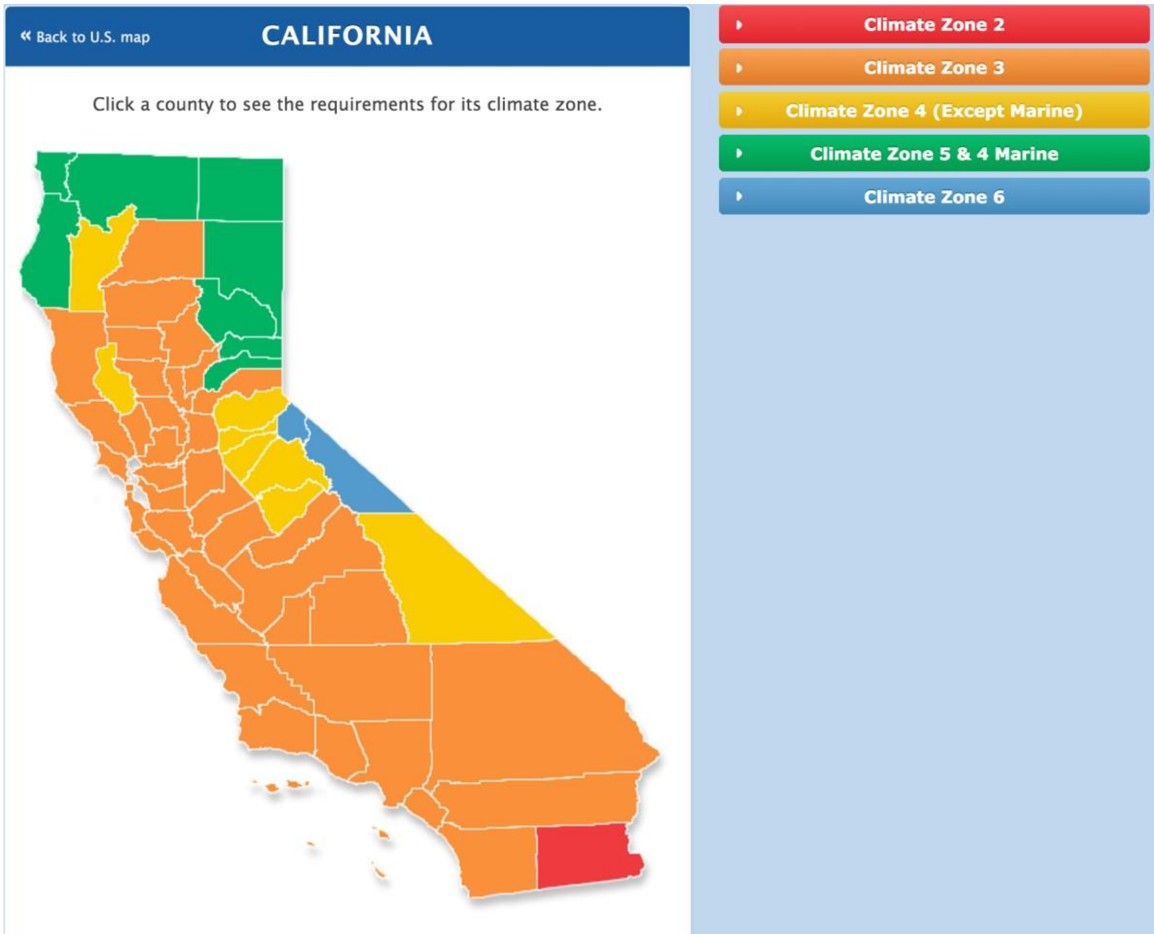

Figure 23 Figure 23 Map of California indicating IECC 2009 climate zone designations. Source: *https://energycode.pnl.gov/EnergyCodeReqs/*

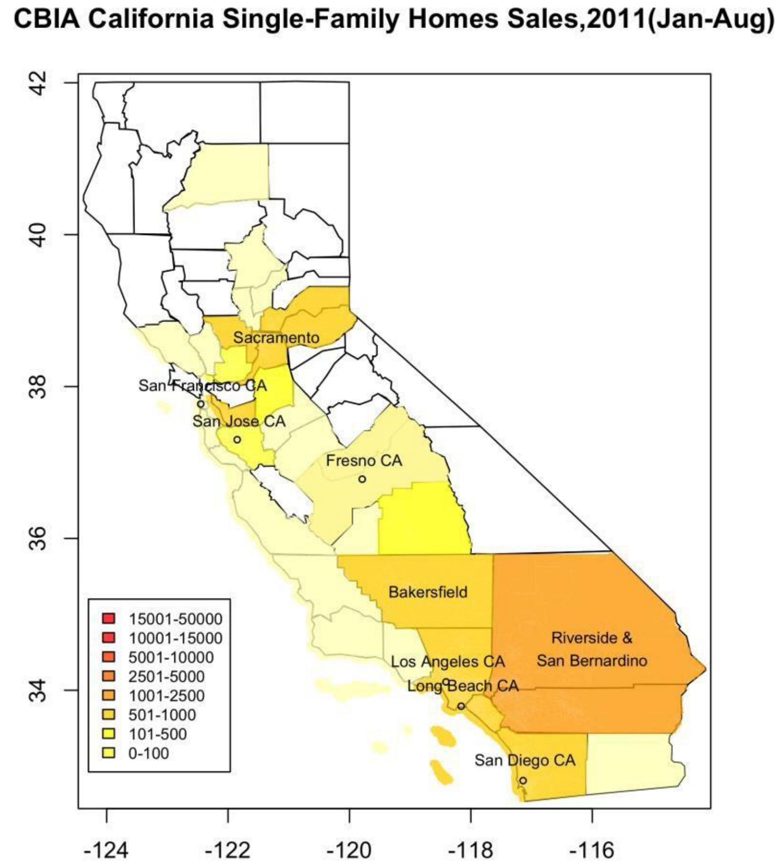

Figure 24 California single-family new home sales, 2011 (January to August). Source: CBIA.

As indicated in Table 3, the IRC 2012 requires use of air impermeable insulation, of varying depths, in sealed and insulated attic assemblies located in nearly all climate zones in CA (exceptions are CZ 2B and 3B when using tile roof finish). This is specifically intended to limit potential moisture issues resulting from condensation on cold roof sheathing surfaces during winter. So, for homes with tile roofs located in the areas of the state with the most development, sealed and insulated attics can be built without any air impermeable insulation. But this is not the case when using other roof finishes, or when building in other climate zones. Furthermore, in CZ 5 and above, which include northernmost CA counties and those in the high Sierra, a class II vapor retarder is required on the warm side of the assembly.

10.2 California Building Code and Common Methods

There are a number of features of the California building energy code, and of typical construction practices in new California homes, that can affect the performance of homes with sealed and insulated attic assemblies. In general, we highlight features that may improve energy performance, but add some additional moisture risk in sealed and insulated assemblies. These code features are described in Section 4.1.3 and are discussed below.

Cool roofs have been shown to lead to lower roof surface and roof assembly temperatures, both in vented and sealed and insulated attics (see Section 7.3.1). This can lead to higher attic air relative humidity (Parker & Sherwin, 1998a). Just like north-facing roof surfaces[22], cool roofs have higher risk for moisture damage, due to their lower solar gains and assembly temperatures. This will tend to increase the risk of condensation and moisture accumulation in the roof assembly in two ways. First, the lower roof sheathing temperatures may lead to more frequent and greater condensation. Second, the reduced heat flux through the roof also reduces the roof sheathing's ability to transfer stored moisture to the surrounding air or other materials.

All *HVAC duct systems* are now required to be reasonably airtight and measured by a certified HERS rater. Furthermore, ducts in vented attics are insulated to a minimum R6 throughout the state. Ducts in conditioned space must have a minimum of R-4.2, but we expect that most builders will continue to use R6, even in sealed and insulated attics. So, code compliant duct systems in new California have are expected to have low thermal losses. This means two things. First, the unintentional partial conditioning of sealed and insulated attic spaces will be reduced. Second, the energy savings potential of the sealed and insulated attic strategy may be lower, at least at a level that has not been measurable in existing field studies (see Section 9.1). If the attic volume is "less conditioned" than would be the case with leaky, uninsulated ducts, then the HVAC system is less likely to remove moisture from the attic, which might lead to increased attic air RH and assembly moisture contents. Lstiburek (2014) discusses this exact issue when recommending partial direct conditioning of sealed and insulated attics with a small supply and return duct. While this is a concern in homes with very tight duct systems, measurements by Hoeschele et al (2015) suggest that ducts in sealed and insulated new California attics were relatively leaky (average around 8%), but with low leakage to outside (<1-2%). This 8% leakage should provide more than ample partial direct conditioning, and it was in fact greater than leakage measured in the vented attic homes. Some natural air exchange across the uninsulated ceiling plane is also expected to promote mixing and partial conditioning, but this effect varies depending on how leaky the house's ceiling plane is.

Radiant barriers are a prescriptive code requirement throughout the state's developing regions, but they are not required in assemblies with insulation in the rafters, because there is no place to mount them. Furthermore, the value of the radiant barrier is in blocking heat transfer from the hot roof deck to the HVAC ducts, but rafter insulation already reduces this temperature difference.

[22] Notably, due to their lower overall solar heat gains, North-facing roof slopes are least affected by changes in surface albedo, due to cool roof finishes. Nevertheless, North-facing roof slopes are at risk from condensation due to their lower temperatures, and any further reduction in heat gain could exacerbate this problem.

Ventilation cooling is a prescriptive code requirement in much of the state's regions with the most development. This approach uses a large fan to vent the home into the attic and will not work for sealed and insulated attics. The alternative is the use of central fan night ventilation systems (sometimes known as economizers), which use a return ducted to the outside, to provide high ventilation rates when beneficial from a cooling perspective. These are only used during the cooling season, and their operation most likely would reduce moisture levels in the home. So, they may provide some limited advantage in a sealed and insulated attic context.

Finally, although not a code requirement, the use of *tile roofing systems* is prevalent across California, with the majority of the market using either direct nailed-to-sheathing or single horizontal 1x1 batten tile arrangements (Parker, 2005b). Tile roof systems reduce heat flux through the roof assembly, and they enhance drying of the whole assembly, as long as no vapor retarding underlayment is installed. As discussed in Section 7.3.2 above, this is the result of radiative properties, increased thermal mass, and roof deck venting. As with cool roofs, this tends to reduce the sheathing temperature, which can increase moisture risk. Yet, due to their increased thermal mass, roof-sheathing temperatures may increase at night relative to asphalt shingle roofs, which could reduce risk of condensation. Notably, roof deck venting enhances the drying potential of the sheathing, which may reduce the risk further.

10.3 Energy Performance

When compared with modern, airtight duct systems in a vented attic, sealed and insulated attics in California may still provide substantial benefit. Energy performance is expected to be roughly equivalent between sealed and insulated attics and prescriptive advanced roof/attic options in Title 24 2016 (see Section 4.1.3.2). System performance can also be expected to improve, such as pull down time, performance at peak load, etc. We expect benefits to be reduced for all advanced roof/attic approaches, relative to a traditional vented attic, as system leakage is reduced close to 0, as in some new California homes (Ring 4 Club, n.d.).

The most recent assessments, comparing advanced roof/attic assemblies to code compliant vented attics suggest average 13% TDV energy savings, with substantial variation by climate zone (more savings in more extreme climates) (see Figure 25). Similar 6-11% reductions in seasonally adjusted HVAC duct thermal losses have been measured in a small subset of such California homes using the ducts in conditioned space approach. In contrast, past simulation studies suggested that energy savings may be small relative to homes with vented attics and tight, insulated duct systems (GARD Analytics, Inc., 2003a; Hendron et al., 2002), and measurements in vented and sealed and insulated attic homes suggested that distribution efficiencies were indistinguishable (Siegel & Walker, 2003). As discussed above in Section 9, the presence and efficiency of HVAC ducts in sealed and insulated attics are the critical elements in determining energy performance. Field measurements of energy performance have indicated that cooling energy reductions in sealed and insulated attics are nearly unmeasurable when duct leakage is low (i.e., <6%). In fact, no field study has demonstrated substantial energy savings in airtight ducts located in sealed and insulated attics. This may be due to limitations of the field study assessment methods, which did not qualify as controlled experiments. These contrasting results are also likely due to inconsistent modeling methods/capabilities, and to poorly executed sealed and insulated designs (i.e., attic and ducts leaky to outside, low insulation).

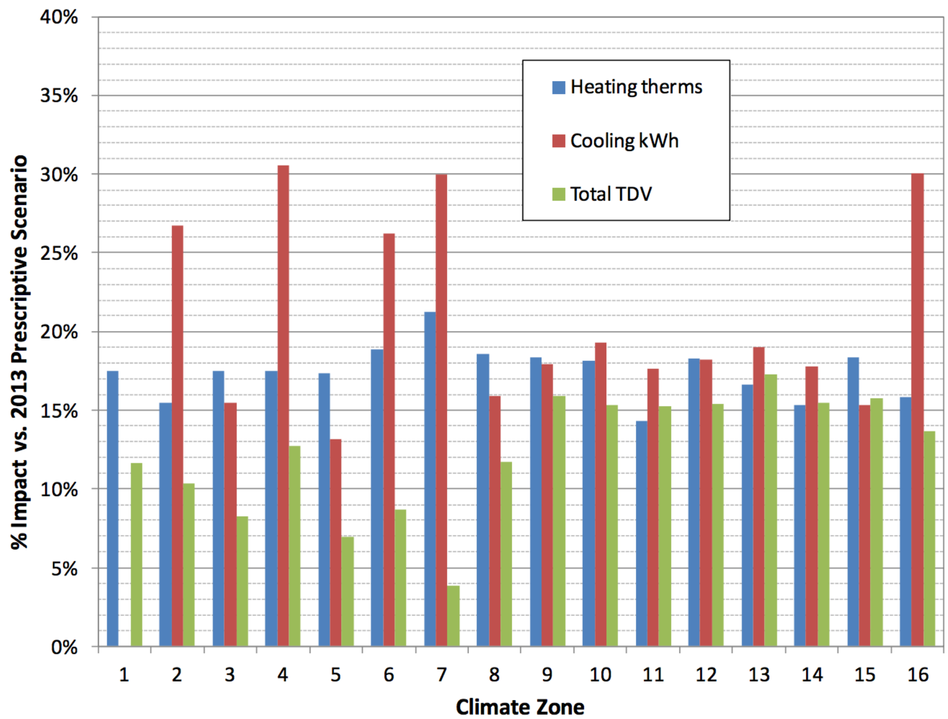

Figure 25 Projected energy savings (heating, cooling and combined time-dependent valuation (TDV)) for ducts in conditioned space across California climate zones compared with the 2013 prescriptive code path to compliance with Title 24 Building Energy Code. Projected savings vary substantially by climate zone and conditioning type. ***Source: Hoeschele et al. (2015).***

New California homes built to the 2016 Title 24 energy code will need to demonstrate either compliance with advanced prescriptive attic/roof options, or TDV energy equivalence to those options. The three prescriptive options all include advanced attic/roof strategies that are designed to reduce attic temperatures or to reduce thermal losses from HVAC ducts. Relative to ducts in a traditional vented attic, all of these approaches are expected to save energy (Wei et al., 2014). As discussed in the energy performance Section 9, sealed and insulated attics are expected to perform similarly to the advanced vented attic options. Limited simulation studies suggest that sealed and insulated attics may perform better than the insulated roof deck HPVA Options A and B, and may have lower performance than the ducts in conditioned space (DCS) Option C. All else being equal, we expect that homes using sealed and insulated attics can provide equivalent energy performance to the other prescriptive options.

What remains to be seen is how builders will comply with these roof/attic code requirements. We know that compliance using the prescriptive paths is very rare (approximately 5% of new construction). But builders using the performance path may still use prescriptive roof/attic assemblies, but seek flexibility in other part of their design. They may also use the sealed and insulated attic approach, or use a traditional vented attic and comply with additional energy saving measures elsewhere in the design.

Given this plethora of design options for code compliance, builders/designers should consider sealed and insulated attic designs using air permeable insulation if:

- Complex roof designs make provision of adequate vent area impossible or overly complex.
- Complex ceiling configurations or numerous penetrations make air sealing at the attic floor undesirable, or complicate construction of dropped ceiling or attic duct chases.
- HVAC subcontractor is not familiar with providing high performance equipment and distribution systems.
- They are building in locations currently recognized by the IRC as requiring no air impermeable insulation.
- They want low costs and the highest performance.
- They want to avoid construction of chases and other such oddities to contain ducts within a vented attic.
- They want to avoid specification of complex and unfamiliar assemblies, including phase change materials and vented roof decks.
- They want ducts remain accessible for inspection, additions and repairs.
- They want the attic to be available for storage space.

10.4 Moisture Performance and Durability

Moisture in sealed and insulated attics can be a concern in some CA climates, but a lack of field data and the highly conservative nature of extant modeling and analysis (and resultant IRC code requirements) makes this hard to evaluate. We expect moisture risk in sealed and insulated attics to be highest in the marine and cold climates of California. Marine climates have higher outdoor humidity, which can contribute to elevated indoor levels. Cold climates, while generally having drier outside air, also have the most potential for roof sheathing surfaces to be below the dew point. Hot-dry climates, such as those in the most populous regions of the state, have not been the subject of moisture investigations in sealed and insulated attics, because they are largely considered to be low-risk locations. Nevertheless moisture problems have been demonstrated even in hot-dry desert locations due to cool roof surfaces and night sky heat losses from flat roofs (Rose, 2007).

But as noted above, there are a number of features of the California Building Energy code and of typical construction practice that may increase the risk of moisture damage in sealed and insulated roof assemblies, particularly in cases using only air permeable insulation materials. Furthermore, indoor moisture levels are expected to be elevated in new, high performance homes that comply with current Title 24. Nevertheless, we believe that construction of sealed and insulated attics consistent with IRC 2012 requirements (see 4.2.1) will mitigate most of the expected moisture risks. Our simulation study of moisture and energy in sealed and insulated California attics will further explore the moisture implications of using only air permeable insulation in sealed and insulated attic assemblies throughout the state.

We are unaware of any moisture performance field assessments of sealed and insulated attics in California. Some field measurements in five homes have been made by ORNL in partnership with Owens Corning and KB Homes in San Marcos, CA (Carpino, 2014), but no data have been published from these efforts, to-date. Almost all assessments and reports of moisture issues in sealed and insulated attics covered in Section 8.4 have come from cold, mixed-humid or hot-humid climates. This does not mean that dry climates, such as California, are immune to moisture issues resulting from sealed and insulated roofs. In fact, Ueno & Lstiburek (2015) described sealed and insulated attic moisture issues in one such California home (CZ 3A) insulated with fibrous insulation.

The only simulation study of attic moisture performance that has focused on California climate zones was done by Lstiburek & Schumacher (2011), and its main focus was on vented attics, with insulation both on the attic floor and at the roof deck per prescriptive Options A and B. They performed one relevant analysis of a "vented" attic with very low air exchange with outside, which is akin to a sealed and insulated attic. This approach led to increased winter sheathing moisture contents in CZ 12 and 16 (the only zones assessed), and in CZ 16, sheathing MC was in excess of 40% for over a month during the winter. This is unacceptable, but in the milder climate zones it is expected that sheathing MC will be elevated but remain below fiber saturation, unless indoor humidity is too high.

Ultimately, it is the indoor humidity that most directly affects moisture risk in sealed and insulated attics. Indoor moisture levels are determined by a combination of outside humidity, ventilation rates, dehumidification (if any) and indoor sources and sinks. Yet, in new high performance homes (e.g., such as those being built to meet Title 24), lower air exchange rates, higher occupant densities, and reduced cooling system operation due to smaller sensible loads, will tend to drive indoor humidity higher for any outdoor climate. In fact, incorporation of HVAC ducts in conditioned space has been shown in simulations to increase indoor humidity levels in this context (Rudd et al., 2013). Even climates such as Los Angeles have been linked with elevated indoor humidity in very high performance homes (Martin, 2014). Consistent with these concerns, indoor humidity conditions during the winter were elevated in 8 of 11 deep energy retrofits monitored in California climate zones 3C and 3B by Less et al. (2012). These increased moisture levels may pose additional risk for sealed and insulated attic homes. Our research will assess the need (if any) for supplemental moisture control in these homes.

In order to best manage moisture issues in sealed and insulated attics insulted with fibrous insulation, we recommend:

- Control indoor humidity levels:
    - Continuous outside air ventilation, as required by the Title 24 energy code.
    - Removal of indoor moisture sources at their point of origin (i.e., kitchen, bathroom and laundry), through use of local exhaust fans (also required by the T24 code). All fans should be quiet, such that their use is not discouraged.
- Use of IRC guidelines for air impermeable insulation, as required by climate zone and roof finish type.

11 Summary of Key Issues for California Sealed and Insulated Attics

Here we summarize the key findings of this literature review and analysis, focusing on the thermal, moisture and energy performance of sealed and insulated attics in California climates.

Thermal. Sealed and insulated attics are expected to maintain attic air temperatures that are similar to those in the house within +/- 10°F. Thermal stress on the assembly, namely high shingle and sheathing temperatures, are of minimal concern. In the past, many sealed and insulated attics were constructed with insufficient insulation levels (~R-20) and with too much air leakage to outside, leading to poor energy performance. To ensure high performance, sealed and insulated attics in new California homes should be insulated at levels at least equivalent to the flat ceiling requirements in the code, and attic envelopes and ducts should be airtight. We expect that duct systems in well-constructed sealed and insulated attics should have less than 2% HVAC system leakage to outside.

Moisture. Moisture risk in sealed and insulated California attics will increase with colder climate regions and more humid outside air in marine zones. Risk is considered low in the hot-dry, highly populated regions of the state, where most new home construction occurs. Indoor humidity levels should be controlled by following code requirements for continuous whole-house ventilation and local exhaust. Pending development of further guidance, we recommend that the air impermeable insulation requirements of the International Residential Code (2012) be used, as they vary with IECC climate region and roof finish.

Energy. The energy benefits of sealed and insulated attics depend on the insulation and airtightness of the attic and ducts. Existing homes with leaky, uninsulated ducts in the attic should have major savings. When compared with modern, airtight duct systems in a vented attic, sealed and insulated attics in California may still provide substantial benefit. Energy performance is expected to be roughly equivalent between sealed and insulated attics and prescriptive advanced roof/attic options in Title 24 2016. System performance can also be expected to improve, such as pull down time, performance at peak load, etc. We expect benefits to be reduced for all advanced roof/attic approaches, relative to a traditional vented attic, as system leakage is reduced close to 0. The most recent assessments, comparing advanced roof/attic assemblies to code compliant vented attics suggest average 13% TDV energy savings, with substantial variation by climate zone (more savings in more extreme climates). Similar 6-11% reductions in seasonally adjusted HVAC duct thermal losses have been measured in a small subset of such California homes using the ducts in conditioned space approach.

Given the limited nature of energy and moisture monitoring in sealed and insulated attic homes, there is crucial need for long-term data and advanced modeling of these approaches in the California new and existing home contexts.

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