# White Roofs and Moisture in the US Desert Southwest

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## ABSTRACT

*Roof assemblies in the US desert Southwest have been instrumented for temperature and humidity. The low-slope roofs are composed of R-38 insulation installed directly beneath wood product sheathing boards, and are covered with a built-up roof and topped with a very reflective white coating. The air temperature at the underside of the sheathing remained very cold from December through March, rarely rising above the outdoor air temperature even in the middle of the afternoon. Observations confirm the presence of water in the insulation of some of the roof assemblies. Measured values showed high humidity (average RH>80% for several weeks during the winter) at the interface between the insulation and sheathing in some of the roof assemblies.*

*This report presents theory as well as measured and modeled values indicating the "white roof problem". With highly emissive upward-facing surfaces in clear-sky areas, the infrared loss from a surface to the sky is great; indeed, with high solar reflectivity, the solar gain cannot compensate for the sky loss. Since infrared radiation balance measurements are not available for this site, local airport cloud-cover measurements are used as a surrogate. Measured values of temperature and humidity from winters 2004-2005 and 2005-2006 are presented. Modeled values that account for sky radiation, solar radiation, conduction and surface convection are used to explain the measured values.*

## BACKGROUND

An investigation was begun in the winter of 2004-2005 into the possibility of moisture problems in residential roof assemblies in the desert southwest after reports of cracking at the ceiling level. This cracking was determined to be a common phenomenon caused by truss uplift, or the natural longitudinal dimension change in top chords and bottom truss chords in insulated assemblies. A preliminary temperature and relative humidity investigation showed evidence of high humidity and water accumulation between the insulation and sheathing in some cases of original construction, prompting a more thorough investigation. That preliminary investigation, in 2004-2005 was not under the direction or supervision of this research project.

The Building Research Council was asked to conduct a one-winter campaign of monitoring and analysis of seven roof assemblies for temperature and moisture effects. This paper contains the findings and conclusions from the October 2005 to March 2006 monitoring campaign, and references findings from the previous campaign.

## THEORY

There are two dominant elements in the radiant exchange affecting buildings: solar gain and long-wavelength (infrared) exchange with the sky. The steady state heat balance equation for a roof may consist of these principal elements:

$$\alpha Q_{solar} + C_a(T_i - T_s) = h(T_s - T_o) + \sigma(\varepsilon_s T_s^4 - T_{sky}^4)$$

where

$\alpha$ = solar absorptance
$Q_{solar}$ = solar insolation, W/m$^2$
$C_a$ = thermal conductance of the insulated roof assembly, W/m$^2$·K

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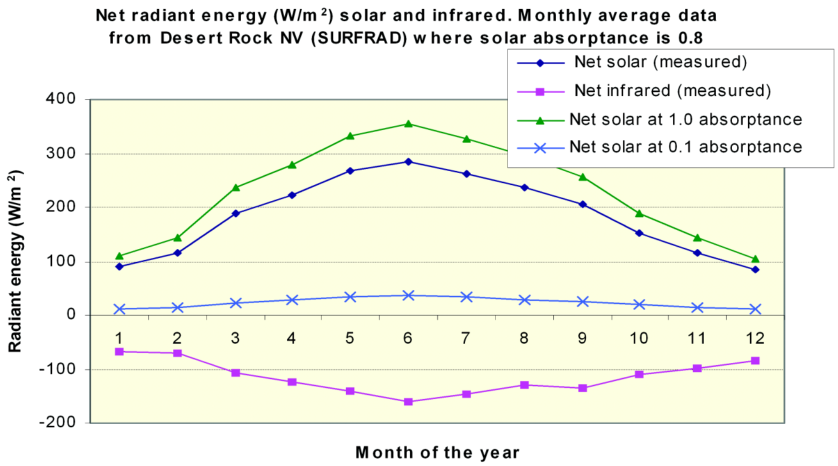


***Figure 1*** *Radiant energy exchange, solar and infrared, at Desert Rock, Nevada. Solar absorptance at the site is 0.8.*

$T_i$ = indoor temperature, K

$T_s$ = surface temperature, K

$h$ = surface air film conductance, W/m$^2$·K

$T_o$ = outdoor air temperature, K

$\sigma$ = Stefan-Boltzmann constant $5.678 \times 10^{-8}$, W/m$^2$·K$^4$

$\varepsilon_s$ = surface emissivity

$T_{sky}$ = sky temperature, K

A transient heat balance would include a storage term.

In desert areas, the clear sky can lead to cooled surfaces because of the outward flux of long-wave (infrared) radiation from the relatively warm roof surface to the relatively cool sky. It is often presumed that radiant heating from the sun can compensate for this cooling effect with a strong heating effect during the day. Data in this report indicate that infrared exchange with the sky may dominate over solar gain, where the sky is clear and the roof has a high solar reflectance.

The principal US effort to measure radiant exchange that distinguishes solar from infrared exchange is conducted by NOAA through the SURFRAD program.[1] There are seven US sites of SURFRAD, and the only Southwest US site is the site at Desert Rock NV. Net radiant exchange from that site is shown in Figure 1. This figure shows solar effects increasing through the summertime and diminishing in the winter. The net of the measured solar and infrared effects is positive, meaning that the excess heat will heat the air, drive heat into the soil and provide heat for organic metabolism. This positive effect occurs because the solar absorptance at the site is 0.8. If the surface were reflective, with an absorptance of 0.1 (See Figure 1), such as with the roof coatings in this study, then the net solar energy at the surface would be only one eighth of the measured value, and the net effect would be a strong cooling effect of the surface, which is what the measured values show in this study.

The effect of long-wave radiant exchange is regulated by the emittance of the roof surface. Most painted surfaces have an emittance of 0.90, so they are actively engaged in infrared radiant exchange with the sky. The effect of outdoor air temperature is strong—only a thin air film acts as thermal resistance between the roof and the outdoor air temperature. The effect of indoor air temperature is weak in a well-insulated building.

The following conditions point toward cooling of roof assemblies:

1. Wintertime conditions, because of low outdoor temperature,
2. White painted surface, because of the low solar absorptance combined with the high infrared emittance,
3. Low-slope roof construction with a parapet, because the roof "sees" the coldest part of the sky (overhead) and is protected from "seeing" the warmest part of the sky (the horizon) and
4. Well-insulated construction, because heating from indoors does not affect the roof surface.

All four of these conditions are found in the roofs in this study.

Wetness in building assemblies is related to temperature, with cold surfaces being wetter and hot surfaces being drier. The relation between temperature and moisture content of wood products (such as the OSB sheathing in the study houses) is expressed in the sorption isotherm[2]. Allowable wetness thresholds for various materials are not determined. However, the International Energy Agency Annex 14 (1991) has determined that a 30-day average surface relative humidity over 80% is a reasonable choice of threshold.[3] This same

1. http://www.srrb.noaa.gov/surfrad/

2. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.htm Chapter 3

3. http://www.kuleuven.ac.be/bwf/eng/publications_04.htm

threshold has been adopted by ASHRAE Standard 160P, now under public review.

Akbari and Konopaki (1998) hinted at the possibility of moisture problems in reflective flat roof surfaces: "It has been stated that in hot and humid climates, cold roofs may experience condensation problems. During the day, the roof and attic do not heat up enough to drive off the possible condensed moisture of the previous night. This may have a negative impact on the lifespan of the roof." They give no indication of where they found these statements of possible condensation problems.

Designers of building envelopes are provided with little guidance regarding solar and long-wave radiant effects. *2005 ASHRAE Handbook—Fundamentals* Chapter 28 "Climatic Design Information" does not provide climatic data pertinent to radiant effects on opaque building surfaces. Designers who make use of ASHRAE Standard 90.1 or LEED-NC are guided toward use of the Solar Reflective Index (SRI), a standard practice described in ASTM E1980. SRI calculations make several assumptions, including an assumed "sky temperature" of 300K. If the actual sky temperature is lower than 300K, then the actual long-wave radiant cooling of the roof surface will be greater than estimated and the risk for high moisture in the roof assembly will be increased.

**Table 1. Apparent Sky Temperature, Monthly Average, Calculated from Measured Longwave Exchange at Desert Rock, Nevada (SURFRAD)**

| Month | (°C) | (K) |
|---|---|---|
| Jan. | –6.5 | 267 |
| Feb. | –6.1 | 267 |
| Mar. | –8.4 | 265 |
| Apr. | –6.5 | 267 |
| May | 0.8 | 274 |
| Jun. | 2.1 | 275 |
| Jul. | 11.6 | 285 |
| Aug. | 10.0 | 283 |
| Sep. | 0.9 | 274 |
| Oct. | –2.4 | 271 |
| Nov. | –8.5 | 265 |
| Dec. | –11.9 | 261 |

Measured values of net long-wave radiant exchange from the SURFRAD program at Desert Rock NV permit calculation of the effective sky temperature at that location. Monthly average sky temperatures at that site are shown in Table 1.

## SETUP

### Roof Assembly

This paper reports on the temperature and moisture findings in five individual houses with Type 1 roof assembly. See Figure 2. Roof assemblies with different construction were monitored during the same period, but in smaller numbers than the type reported here—see discussion section below. All of the homes were constructed after 2002. They are one-story houses with a parapet surrounding the roof on all sides. Because of the parapets, the view factor for the roof included most of the coldest part of the sky (zenith) and excluded the warmest part, the horizon. The roof pitch was approximately 3/8" per foot to scuppers. There was no appearance of roof leaks. The truss roof structure spanned approximately 30'. The roof covering was 7/16" OSB sheathing, built-up roof, and applied coating that was very white. The only equipment on the roof typically was a solar-assisted hot water heater.

The roof construction consisted of R-38 unfaced fiberglass insulation held in place with wires fastened to the truss web members. There were supply ducts located in the air space below the insulation. There was no vapor protection below the sheathing, other than two coats of latex paint applied to the gypsum wallboard ceiling.

### Instrumentation

The instruments used in this investigation are self-contained battery-operated temperature and relative humidity dataloggers (Hobo Pro, Onset Corporation). Placement of the sensors was achieved by cutting a hole, approximately 12" x 6" in the roofing and sheathing, placing the dataloggers an arm's length from the opening at the underside of the sheathing, above the fiberglass insulation. Since the fiberglass insulation was held in place by wires below, the air space was compressed around the datalogger. The sheathing was replaced and the roof was repaired to watertight condition. Indoor T/RH dataloggers were placed at a principal common

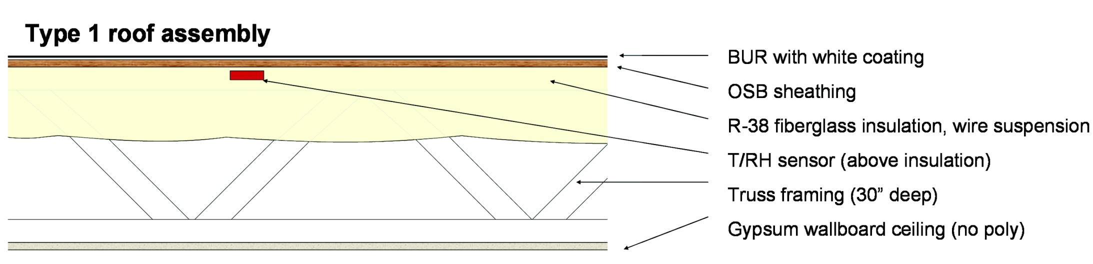


***Figure 2*** *Type 1 roof configurations in this study.*

room inside. Outdoor sensors were placed usually under a porch, in a location protected from rain and sun. The data collection interval was 1 hour.

## FINDINGS

### Winter 2004–2005 Data

The data campaign that is the focus of this report was conducted during winter 2005-2006. Preliminary data was collected by others the previous winter using instruments and protocols similar to those of the study winter. Winter 2004-2005 was slightly colder than winter 2005-2006. Average outdoor temperature from Tucson International Airport for the dates November 1, 2004 through March 31, 2005 is 55.3°F. For winter 2005-2006, on the same dates, the average outdoor air temperature was 57.1°F. There is no satisfactory way to compare sky clarity for the two winter seasons.

Data from November 2004 through January 2005 are shown in Figures 3 and 4 for type 1 roof construction. Figures 3 and 4 show:

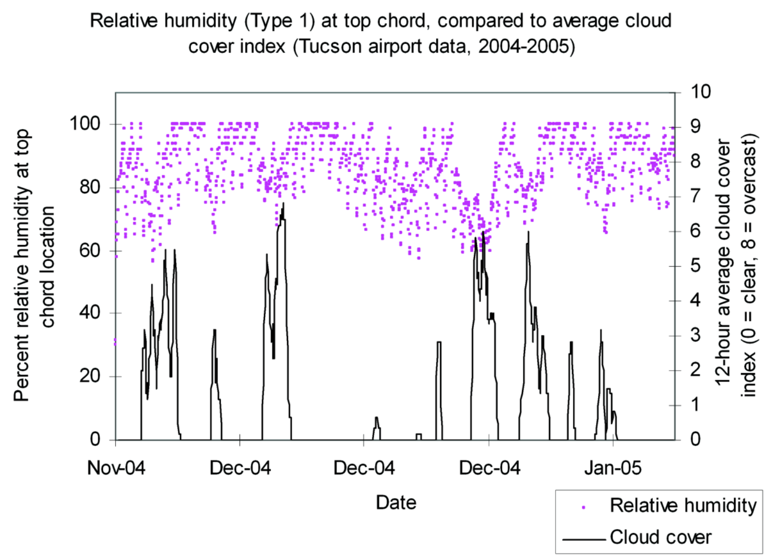


*Figure 3* *Temperature at the top chord minus outdoor air temperature (Type 1 roof assembly) compared to 12-hour average cloud cover index. The top chord location is colder than the outdoor air temperature practically throughout the monitoring period. The top chord location is warmest during periods of cloud cover.*

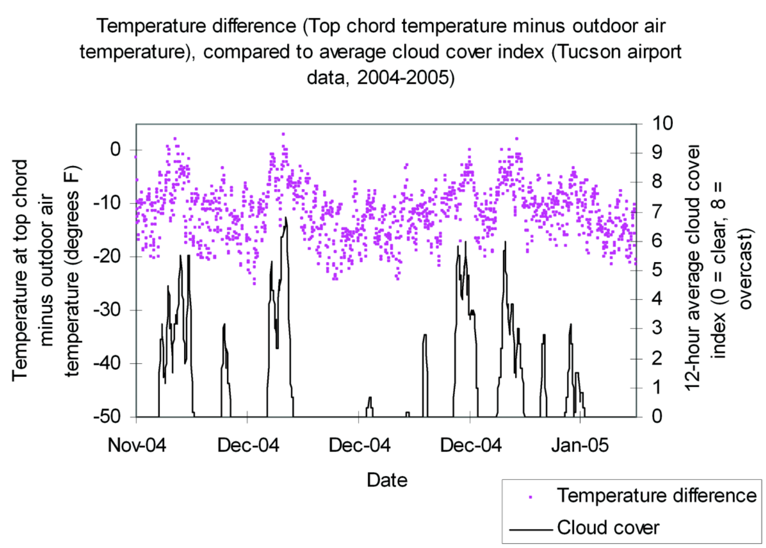


*Figure 4* *Relative humidity at the top chord location (Type 1 roof assembly) compared to 12-hour average cloud cover index. The top chord RH reaches 100% except on days with cloud cover.*

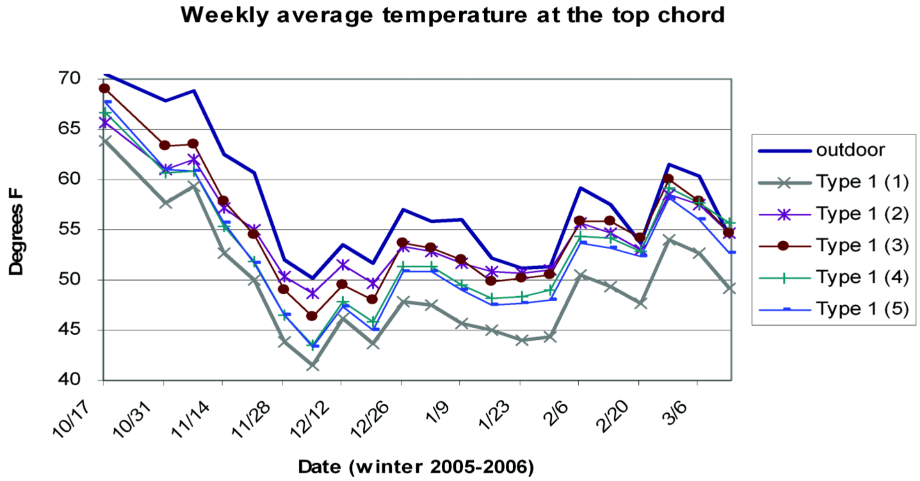


***Figure 5*** *Average weekly temperature at the top chord location for five attic assemblies.*

**Table 2. Measured Values of Temperature and Relative Humidity, Averaged over the Data Collection Period—October 13, 2005 to March 21, 2006 for Five Houses[*]**

| | Average Temperature at Top Chord, °F | Avg. Temp. Depression (Outdoor Air Temperature Minus Top Chord Temperature), °F | Average Relative Humidity at Top Chord | Average Indoor Relative Humidity | Average Indoor Temperature, °F | Average Indoor Vapor Pressure, psi |
|---|---|---|---|---|---|---|
| Type 1 (1) | 49.7 | 8.2 | 79.3 | 33.6 | 71.8 | 0.131 |
| Type 1 (2) | 54.8 | 3.1 | 60.4 | 28.3 | 71.5 | 0.106 |
| Type 1 (3) | 55.0 | 2.9 | 62.9 | 31.4 | 69.0 | 0.112 |
| Type 1 (4) | 53.2 | 4.7 | 57.7 | 30.6 | 72.3 | 0.121 |
| Type 1 (5) | 52.6 | 5.3 | 60.5 | 44.6 | 67.3 | 0.147 |
| Outdoor | 57.9 | — | 28.4 | — | — | 0.089 |

[*] Vapor pressure values calculated from temperature and relative humidity.

- Type 1 roofs experienced high RH. At nighttime, the RH values reached 100% as a wintertime maximum in three of the five units
- RH values of 100% typically occurred on nights with no cloud cover.
- The reason for high RH was low temperatures. The temperature at the top chord location remained lower than the outdoor air temperature practically throughout the monitoring period.
- The temperature at the top chord location was higher during periods of cloud cover, and lower when the sky was clear. This provides demonstration that, with high solar reflectance, long-wave radiant cooling to the sky exceeds the heating effect of solar gain.

These measured values matched anecdotal evidence of water accumulation in the insulation.

## Winter 2005–2006 Data

Prompted by the high RH values seen in the preliminary data, a wintertime campaign was undertaken to measure temperature and humidity at several locations in several roofs. The temperature results, shown as weekly average temperatures, are presented in Figure 5 and Table 2.

In Figure 5 we see the following:

- The weekly average temperature at the top chord, i.e. at the underside of the roof sheathing, was, in all cases, colder than the average outdoor air temperature.
- There was a considerable range of average temperature depressions (temperature outdoors – temperature at the top chord) below outdoor temperature. The house named here as Type 1 (1) was the case with the greatest temperature depression.
- The average temperature depression varied from 2.9ºF, Type 1 (3) to 8.2 ºF (Type 1 (1)).

Temperature differences are presumed to be due to particularities of insulation placement, sensor placement, roof conditions, and indoor temperature, but there is no

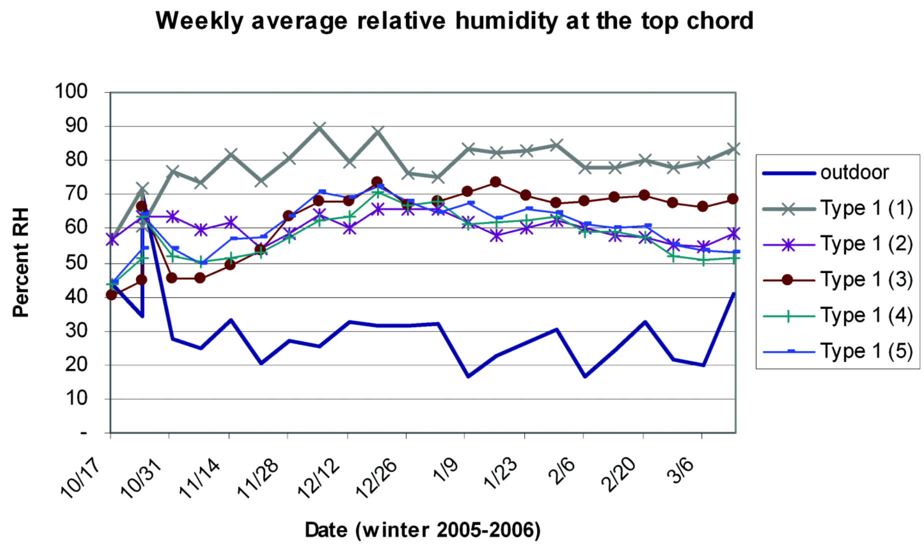


***Figure 6*** *Average weekly relative humidity at the top chord location for five attic assemblies.*

means to account for those particularities at this time. The sensors which took the measurements have been retrieved from their locations.

These temperature results and temperature depression results are summarized in Table 2.

There is a wide variation in average relative humidity at the top chord location, as seen in Table 1 and in Figure 6. We may note the following:

- The case Type 1 (1) had the highest average RH at the top chord, and this is maintained weekly through the winter. The average top-chord RH approaches 80%, and it sees several continuous weeks with average RH in excess of 80%. The case Type 1 (1) was also the coldest case, see Figure 5.
- The remaining Type 1 cases had high relative humidity, but the RH remained below 80% on average. 80% RH is used as a threshold surface relative humidity value by ASHRAE Standard 160P, currently under public review.
- Case Type 1 (1) also had the second-highest indoor relative humidity and indoor vapor pressure. Case Type 1 (5) had high indoor RH and indoor vapor pressure, but this did not translate into particularly high RH at the top chord location.

## DISCUSSION

### Hourly Averages

To further inspect the wettest and driest conditions found in this study, Figure 7 shows the hour-by-hour average of temperature, relative humidity and vapor pressure in three locations (outdoor, indoor and top chord) for the wettest case type 1 (1). The period of data collection was 10/13/05 to 3/21/06. Lines indicating plus and minus one standard deviation (1) of all the data points in that hour through the data collection period are shown.

The top chord location is warmer than the outdoor air from 9am until 3pm. At 7pm, the temperature at the top chord location is (on average) 20 degrees Fahrenheit colder than the outdoor air temperature. For most of the night, it remains approximately 10 degrees F colder than outdoors. The RH climbs through the night, indicating probable accumulation of moisture on the underside of the sheathing, reaching a maximum at approximately sunup. The RH falls during the sunny part of the day.

The vapor pressure results are difficult to interpret. One expects to see vapor pressure in any building cavity to have a value between the average vapor pressure outside and the vapor pressure inside, by conservation laws. Through the monitoring period, the average vapor pressure values were:

- Outdoor 0.066 psi
- Indoor 0.130 psi
- Top Chord 0.154 psi

These results are most likely due to large quantities of moisture stored in the sheathing during nighttime, with the sheathing reaching equilibrium with the surrounding environment. The disequilibrium found during the daytime is transient.

### Other Assemblies

Figure 8 shows three other assemblies that were part of the study. Table 3 shows the results with these assemblies. For the study period Winter 2005-2006, additional cases included:

- A single case of type 1a construction, similar to Type 1, but with five 4” x 14” vents placed in the roof. No provision was made for an air space beneath the vent.

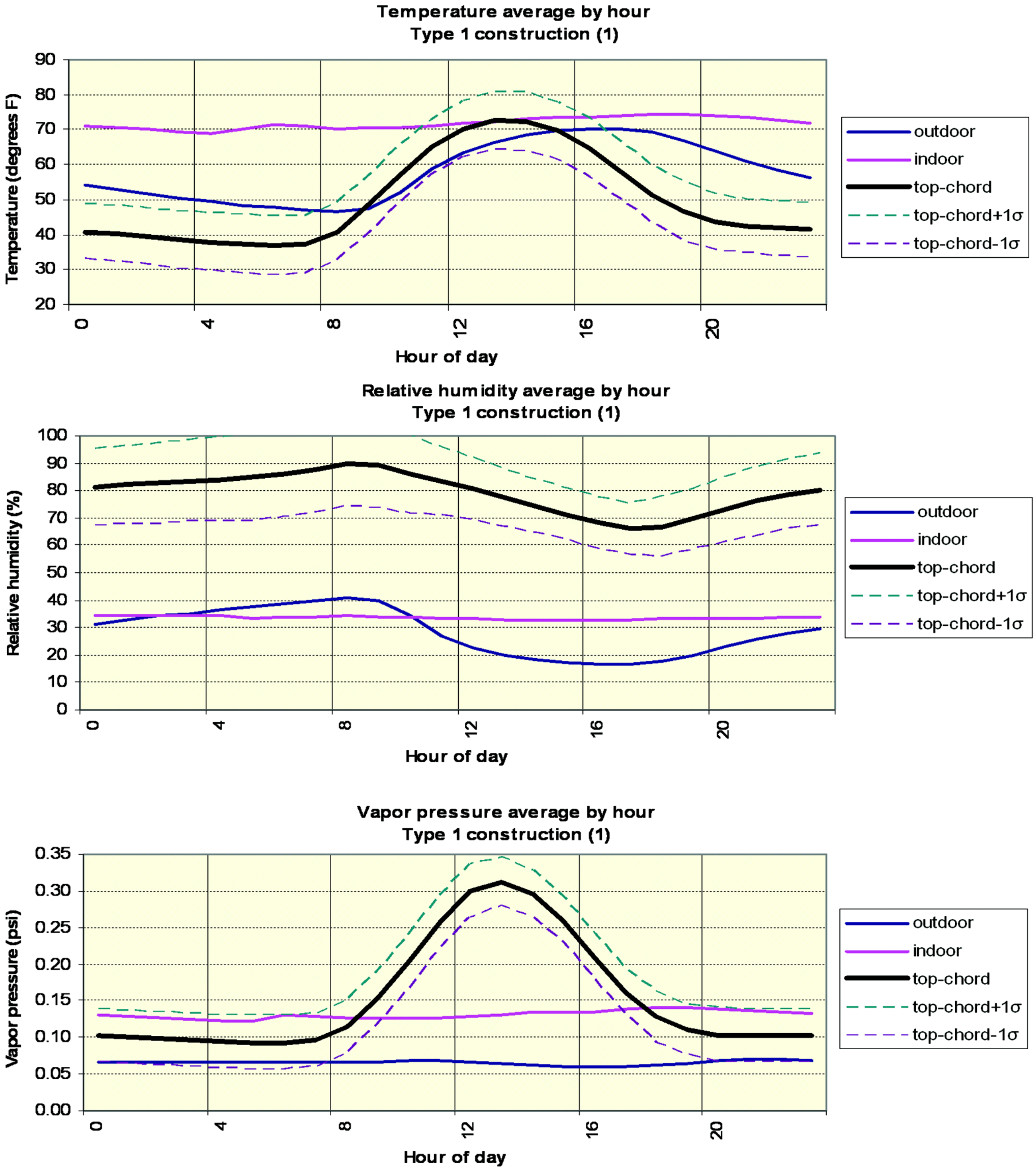


***Figure 7*** *Hour-by-hour averages of temperature, relative humidity, and vapor pressure for Type 1 (1). Dashed lines represent the values plus and minus one standard deviation (σ) from the mean.*

- A single case of Type 2 construction, with no fiberglass insulation, no ventilation, and cellulose insulation (approx. 12”) at the ceiling, and
- A single case of Type 3 construction, with cellulose insulation at the ceiling and a 4’ wide strip of fiberglass insulation removed for the length of the building.

The type 1a results are consistent with those found in Type 1. The Type 3 results show low RH, due largely to the high attic air temperature, a result of having a cavity that is bounded by insulation layers above and below. The Type 2 results show dry construction. Reasons for the low cavity RH in Type 2 construction could not be determined from the single instance, but may be due to 1) use of a sorbent (buffering) insulation material, 2) having an air cavity high in the truss space, potentially in air exchange with the outdoors at the parapet, 3) low indoor RH, or 4) other as-yet unexplored reason.

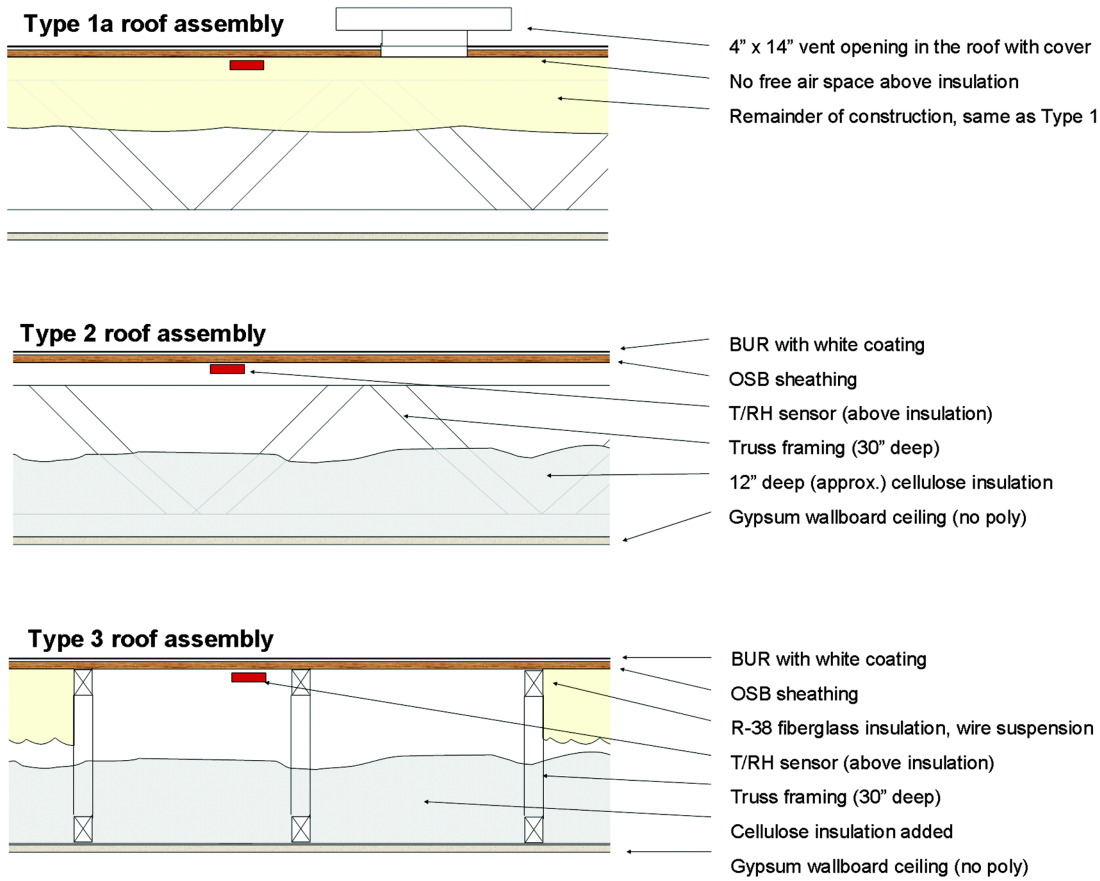


***Figure 8*** *Other assemblies included in the study.*

**Table 3. Measured Values of Temperature and Relative Humidity, Averaged over the Data Collection Period—October 13, 2005 to March 21, 2006 for Additional Constructions***

| | Average temperature at top chord (°F) | Avg. temp. depression (outdoor air temperature minus top chord temperature, °F) | Average Relative Humidity at Top chord | Average Indoor Relative Humidity | Average indoor temperature (°F) | Average indoor vapor pressure (psi) |
|---|---|---|---|---|---|---|
| Type 1a | 50.4 | 7.5 | 67.1 | 28.7 | 71.2 | 0.109 |
| Type 2 | 53.5 | 4.4 | 40.2 | 25.6 | 72.3 | 0.101 |
| Type 3 | 59.8 | –0.9 | 33.1 | 28 | 70.1 | 0.103 |
| Outdoor | 57.9 | — | 28.4 | — | — | 0.089 |

* Vapor pressure values calculated from temperature and relative humidity.

## CONCLUSIONS

Preliminary data from winter 2004-2005 and from case Type 1 (1) indicate that excessively low temperatures may occur on the underside of white roof structures with clear skies. Low temperatures may lead to excessively high humidity (>80% RH, monthly mean basis) in the roof cavity, even with indoor humidity below 35%.

Other roof assemblies with ostensibly the same construction may have high humidity (cavity RH between 60% and 70%, winter average) but not excessively high. The differences in construction or instrumentation that led to these different findings were not able to be determined.

Climate data for the site that permits the solar and the long-wave radiant effects to be distinguished were not available for this study. Such data are available only from seven sites in the US.

No conclusions are drawn from the single cases using Types 1a, 2 and 3 construction.

## RECOMMENDATIONS

Researchers, designers, builders and other should be on the lookout for excessive wetness in well-insulated roof systems with roof coatings of high solar reflectivity in areas with clear skies.

Researchers should encourage measurement of long-wave radiant exchange, and monitoring at more sites than are currently operating. Developers of hygrothermal programs should move toward incorporation of this data as it becomes available.

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