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Field Performance of Unvented Cathedralized (UC) Attics in the USA*

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ABSTRACT: This article reports on field experience of unvented cathedralized (UC) attics in several environments in the United States. Traditionally, in some regions of the country, because of high water tables or the risk of flash flooding and lower cost, slab on grade construction is a preferred mode of construction. Mechanical equipment for air conditioning and distribution ducts are usually located in the attic spaces to conserve space. Conventional construction involves providing insulation on the floor of the attic and venting the attic space to the outside. The loss in efficiency in operation of the equipment and through duct leakage is no longer sustainable. Insulating the attic roof itself and blocking of ventilation to the outside transfers the air and thermal energy controls from the boundary with the living space to the plane of the roof. The air distribution systems now fall within conditioned space, which increases their efficiency, durability, and maintainability.

While design criteria vary for different climatic regions, UC attics can be insulated in various ways and by using different vapor diffusion resistance strategies of the roof assemblies depending on the climate. The field data presented in this article include measured temperature of asphalt shingles, and thermal and moisture conditions of attic spaces and roof sheathing, as well as air leakage rates. This is of interest for determining probable roofing durability. A more complete understanding of the hygrothermal performance of the assemblies was gained through these measurements.

KEY WORDS: attics, unvented attics, unvented cathedralized attics, attic venting, building enclosure, energy efficiency, building durability, shingle temperature, air leakage, infiltration, duct leakage, roof, roof assembly, roof sheathing, roof sheathing temperature, roof sheathing moisture content.

^{*}As this article specifically reviews American experience, the customary SI are placed together with the traditional inch-pound units and the latter are left in tables and graphics. †E-mail: info@buildingscience.com

INTRODUCTION

RADITIONALLY, IN SOME regions of the United States, because of high water tables or the risk of flash flooding and lower cost, slab on grade construction is a preferred mode of construction for residential buildings. Mechanical equipment for air conditioning and distribution ducts are usually located in the attic spaces for convenience and to conserve space. Conventional construction involves providing insulation on the floor of the attic and venting the attic space to the outside. The loss in efficiency in operation of the mechanical equipment located there and losses by duct leakage do not lead to sustainable design. Insulating the attic roof itself and blocking of ventilation to the outside transfers the air and thermal energy control surfaces from the boundary with the living space to the plane of the roof, which results in an unvented cathedralized (UC) attic (Rose, 1995). By this approach, the air distribution system located there is in conditioned space and losses there are of lesser consequence. An UC attic differs from a cathedral ceiling, whether vented or unvented, in that the cathedral ceiling has an interior finish installed beneath the roof rafters and insulation. In the case of an attic, which is usually encumbered with more structural framing, the insulation and framing are left exposed.

The earliest form of UC attics used in residential construction employed polyurethane spray foam insulation adhered directly to the underside of the roof sheathing and gable end walls. This has been especially successful in hot–humid regions to remedy moisture-related problems caused by the condensation of moist air on cool supply air ducts or on gypsum wallboard surfaces (Lstiburek, 1993). While the extra expense of correcting a moisture problem can be easily justified, it is often difficult to use this premium option for price-sensitive new construction. Hence, less expensive insulation systems have been used extensively, such as netted-and-blown cellulose (blown-in-blanket), and strapped-in-place fiberglass batts. The spray foam application inherently eliminates air movement, whereas the fibrous insulation applications allow air movement which, depending on the sheathing temperature, can lead to moisture condensation under the roof sheathing.

Proper design and choice of materials is needed to avoid long periods of moisture condensation. Of the three materials noted above, fiber glass batts are the easiest to install and they provide a high insulation R-value in a uniform thickness. Spray foam is generally less uniform in thickness than fiberglass batts but more uniform than netted cellulose because the netting droops between framing members. Although it can be applied thicker, spray foam is generally not applied to supply an R-value higher than $20 \, \text{hft}^{2\circ} \text{F/Btu}$ (3.52 m²K/W) whether the foam is of medium density i.e., the foam used for wall applications $1.5-2 \, \text{lb/ft}^3$ (24–32 kg/m³) or open-cell, low density foam

 $0.5 \, \mathrm{lb/ft^3}$ (8 kg/m³). Spray foam applicators generally consider R-20 to be an optimum level, especially considering the air sealing capability of the material. Likewise, cathedralized netted cellulose insulation is generally installed to an effective *R*-value of 22 hft²°F/Btu (3.87 m²K/W).

Properly applied, the UC attic approach provides a high value in energy efficiency, durability, and maintainability. It is more energy efficient primarily because the attic mounted air distribution components are all inside the thermal insulation and the air pressure boundary of the conditioned space. This has been shown to provide substantial benefit in both summer and winter (Rudd et al., 2000; Hedrick, 2003; Hendron et al., 2003). It is more energy efficient because, with many ceiling penetrations and height changes, it is often easier to air seal the building enclosure at the roof line instead of the ceiling. It is more durable and maintainable because the mechanical equipment is inside a mild environment, and the services above the ceiling level are left exposed for easy maintenance, repair, or upgrading. It is safer in fire events and windstorms due to the lack of soffit vents and other vent penetrations that intensify the spread of fire and increase air pressure forces on roof sheathing.

Research on the UC attic approach started with computer simulations, showing that, compared to conventional vented attics with normal duct leakage and code level duct insulation, significant annual energy savings could be realized (Rudd and Lstiburek, 1998). Production prototypes were constructed in Las Vegas in 1996, which underwent extensive testing and performance monitoring (Rudd et al., 1996). In addition to exceeding Energy Star energy performance, the houses met strict criteria for building enclosure leakage, duct leakage, and pressure balancing. Controlled mechanical ventilation was also standard. The success of this approach encouraged the builder to make it standard, and the system was later replicated in Arizona, Texas, Florida, and California. Thousands of dwellings have been constructed in this way and testing and performance monitoring studies have continued.

SCOPE OF THIS WORK

The questions typically asked when discussing the unvented cathedral attics are:

- How much is the insulation under the asphalt roofing increasing their temperature?
- Does this increase affect the durability of the shingles?
- Can the insulation be air and vapor permeable or not?

• Does the placement of insulation affect the requirements for vapor diffusion resistance beneath asphalt roofing materials?

 How do the thermal and moisture requirements vary with the climatic conditions?

To examine the relationships between the construction pattern and the climate, case studies are presented by different climatic regions starting with warm and dry climates.

An important hurdle in California and parts of Arizona was to be able to claim the benefit of having the air distribution ducts inside conditioned space without having to actively condition the UC attic (Walker, 2004). For dwellings with an UC attic, the ceiling is not constructed airtight as it would be for houses with a vented attic. Therefore, there is natural air exchange between the living space and the UC attic. In addition, even though the duct systems are sealed, there is always some leakage, especially at the air handler cabinet, which adds to the indirect conditioning of the cathedralized attic.

If insulation under the roof sheathing is the effective thermal insulation boundary, then heat transfer to and from the air distribution system will contribute to space conditioning rather than being lost to outdoors. Likewise, if the roof sheathing is the primary air pressure boundary, then air leakage into and out of the air distribution system will be inside the primary air pressure boundary and will contribute to space conditioning rather than being lost to outdoors. To prove the point, a two-prong approach was taken:

- (1) The indirectly conditioned UC space may be considered, for the purpose of energy performance, the same as the conditioned space. The small temperature differences measured between the living space and the UC attic provide the evidence to this end. The small differences were measured for both average and peak temperature differences.
- (2) When using the UC attic approach, one needs to provide criteria by which the UC attic could be qualified as having sufficiently low air leakage to the outdoors.

Data were collected and analyzed to demonstrate that the thermal air distribution system, located inside the UC attic, was for all intents and purposes inside the conditioned space. A combination of pressure differentials and air leakage measurements could create a set of criteria to bound the acceptability of a given UC attic construction as one that would corroborate the predicted performance by measured temperature conditions in the attic and the living space.

The next set of studies involve cold climates. Application of the UC attic in cold climates can be especially effective if air distribution ducts are

located in the attic. Heat loss from ducts in cold northern attics is significant (Petrie et al. 2004).

However, when cold temperatures prevail for extended periods, it is doubly important to avoid moisture condensation on roof sheathing. Air impermeable polyurethane spray foam applied continuously and directly to the underside of the roof sheathing and framing is preferred. This keeps interior moisture, carried by air movement, from contacting the cold roof surfaces. There are other methods and materials for installing air impermeable insulation, but whatever is done, the warm moist interior air must not contact the cold roof sheathing or framing (TenWolde and Rose, 1998; Rose and TenWolde, 2002). Many homes in northern cold climates are humidified during winter. Ordinarily, there is no reason to humidify to more than 35% relative humidity (RH). If higher RH conditions exist for extended periods (days to weeks), then a vapor retarder paint or film may have to be considered to protect the surface of vapor permeable insulation.

Finally, the article presents cases of UC attics in hot and humid regions. From first principles, locating ducts inside the conditioned space should have significant benefits in hot–humid climates because moist exterior air is excluded from the space where the air distribution system is located. Air distribution system losses are much greater if return-side duct leakage draws in exterior moisture (latent heat) in addition to sensible heat. More than twice as much energy is required to reduce the air dew point by 20°F (11.1°C) as to reduce the air temperature by that amount.

Yet, the most significant findings about UC attics in hot and humid regions relate to the transient moisture that is frequently deposited on the roof during the clear nights (often called sky radiation effect). It appears that some of this moisture is drawn into the material of the composition shingles, and the laps between them. Solar radiation subsequently heats the roof surface, increasing the water vapor pressure and creating thermal gradients that drive water vapor into the roof assembly. This happens whether the roof is vented or not, hence, this study also contains recommendations for moisture control beneath the shingle layer.

HOT-DRY AND MIXED-DRY CLIMATES

Measurement of pressure differentials, building enclosure air leakage, and hourly monitoring of attic and living space temperatures and RH conditions were made between late July 2002 and January 2003 for ten UC attic houses in Banning, CA.

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Measured Air Leakage of the Building Enclosure

Pressure differentials were measured across the ceiling between the attic and living space, with the attic access hatch closed and the living space depressurized to $-50\,\mathrm{Pa}$ with respect to the outside. If the attic was perfectly sealed to the outside, and the ceiling was sufficiently leaky, the pressure differential across the ceiling would tend to be very small. If the attic was leaky to the outside, the pressure differential would tend toward $50\,\mathrm{Pa}$ across the ceiling.

The total building enclosure leakage at $-50\,\mathrm{Pa}$ pressure differentials with respect to the outside were measured twice; once with the attic access open and once with the attic access closed. The attic-access-open test was the primary test to qualify the entire building enclosure as meeting the established criteria of less than 0.25 cfm per square foot of building enclosure surface area (Lstiburek, 1997), which is the standard envelope tightness goal for energy efficient homes in the US.

The measured results are listed in Table 1. The pressure differentials ranged from a low of 10.6 Pa to a high of 19.0 Pa, with the average being 15.7 Pa. This means that, on average, the roof plane provided about 70% of the pressure drop and that the ceiling provided the rest.

Table 1. Air leakage of the building enclosure and pressure differences for ten houses constructed by one builder in Banning, CA.

Address	cfm50 attic access open (ft³/min)	cfm50 goal (ft ³ /min)	Pass/fail(-) leakage criteria (%)	cfm50 attic access closed (ft ³ /min)	cfm50 diff open-closed (ft ³ /min) (%)	dP attic wrt house (Pa)
476 Brooklawn	1290	1300	1	1050	19	19.0
2300 Birdie	1428	1300	-10	1090	24	17.0
1818 Masters	1825	1750	-4	1534	16	17.0
2356 Birdie	1253	1300	4	1077	14	16.9
2245 Birdie	1295	1405	8	1135	12	14.6
2349 Birdie	1698	1750	3	1458	14	14.7
1826 Masters	1487	1405	-6	1291	13	14.3
1974 Fairway	1515	1405	-8	1266	16	16.9
1698 Masters	1257	1750	28	1170	7	10.6
1927 Fairway	1774	1750	-1	1587	11	15.8
Min			-10		7	10.6
Max			28		24	19.0
Avg	1482	1512	1	1266	15	15.7

Temperature Difference between UC Attic and Living Space

Data loggers recorded hourly temperature and RH in each of the houses listed in Table 1. The data loggers were located near the thermostat and in the attic at a height estimated to be representative of the air duct environment. That height was usually about 4 ft (1.2 m) from the attic floor.

The summary analysis for nine of the ten houses is given in Tables 2–5 and Figures 1 and 2. The owners of the tenth house declined involvement part way through the monitoring period. Outdoor air temperature ranged from 102°F (38°C) during the cooling season and 32°F (0°C) during the heating season.

In Table 2, the most common temperature bin, both at the thermostat and in the attic, was between 74 and 76°F (23 and 24°C) during the cooling season period of monitoring (24-Jul-02 through 14-Oct-03). In Table 3, the most common temperature bin, both at the thermostat and in the attic, was between 70 and 72°F (21 and 22°C) during the heating season period of monitoring (15-Oct-02 through Jan-03).

In Table 4 and Figure 1, most of the hourly temperature samples show that during the cooling season the attic was between -2 and $+6^{\circ}F$ (-1 and $3^{\circ}C$) of the living space, with the largest group between -2 and $0^{\circ}F$ (-1 and $0^{\circ}C$) temperature difference. In Table 5 and Figure 2, during the heating season, the attic was mostly between -2 and $+2^{\circ}F$ (-1 and $+1^{\circ}C$) of the living space, with the largest group between -2 and $0^{\circ}F$ (-1 and $0^{\circ}C$) temperature difference. These are small differences.

Discussion

Based on the data in Table 1, a working benchmark (criterion) for UC attics was postulated as less than 20% difference between the attic access open and closed tests i.e., less than 17 Pa pressure difference across the ceiling with the house at -50 Pa. However, in a study of 33 houses (Table 6), it became apparent that unpredictable differences in ceiling air tightness made it unreasonable to use this measurement as an UC attic criterion.

The ceiling plane air tightness varied greatly because of the number of recessed canister lights, chases, and other ceiling penetrations. These data are shown in Table 6; the records were sorted in the descending order with those that passed the building leakage test by the largest margin. Seventeen houses that passed the primary building leakage test (some by more than 30%) would not have passed the attic tightness criteria, and one house that did not pass the primary building leakage test would have passed the postulated attic tightness test. An additional test was conducted for these houses using a calibrated fan at the attic access in addition to the calibrated

Table 2. Cooling season temperatures at the thermostat location and in the attic.

Air temperature	47	76	16	98	18	18	18	26	19	27	19	74	22	45	23	00	23	356	Ave	rage	% of s	amples
bins (°F)	tstat	attic	tstat	attic																		
64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	2	0	0
68	0	7	10	11	0	1	4	26	15	29	0	0	0	22	0	7	0	15	3	13	0	1
70	4	33	84	76	12	28	61	70	77	59	0	11	24	49	5	25	15	73	31	47	2	2
72	46	88	302	200	90	100	271	200	141	124	57	110	120	148	52	86	74	190	128	138	7	7
74	139	111	429	302	143	127	343	260	159	174	353	200	357	286	234	373	359	413	280	250	14	13
76	135	253	739	411	843	435	539	354	1120	459	893	437	799	401	1338	509	941	459	816	413	42	21
78	438	329	269	274	856	372	657	273	404	331	527	357	589	288	175	256	164	247	453	303	24	15
80	825	428	135	354	24	583	97	387	40	409	126	433	86	373	98	340	7	305	160	401	8	20
82	375	321	3	263	8	296	0	291	0	277	12	318	2	276	61	270	0	184	51	277	3	14
84	21	286	1	80	3	33	0	107	0	72	4	86	0	126	16	85	0	69	5	105	0	5
86	0	114	0	1	0	4	0	4	0	6	0	17	0	8	2	26	0	22	0	22	0	1
88	0	13	0	0	0	0	0	0	0	0	0	3	0	0	0	1	0	0	0	2	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0	0
90+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		Sum:	1928	1974	100	100

Table 3. Heating season temperatures at the thermostat location and in the attic.

Air	47	76	16	1698		18	1826 1927		19	27	19	74	22	45	23	00	2356		Average		% of samples	
temperature bins (°F)	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
56	0	70	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	8	0	0
58	49	79	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	5	11	0	0
60	162	98	0	4	0	0	0	0	0	26	0	0	7	47	0	0	0	0	19	19	1	1
62	65	160	0	57	0	0	2	16	30	28	0	0	78	44	0	0	0	26	19	37	1	1
64	204	326	55	115	0	0	28	85	46	109	0	0	24	25	0	209	8	138	41	112	2	4
66	423	584	133	254	0	21	176	290	115	155	0	7	26	161	328	421	126	462	147	262	6	10
68	882	743	464	453	23	110	727	692	174	274	7	74	180	455	596	655	597	556	406	446	15	17
70	628	434	950	770	193	300	1304	820	751	528	120	203	733	583	742	570	765	588	687	533	26	20
72	269	204	853	698	667	434	277	551	1337	796	1350	1367	807	528	564	399	743	635	763	624	29	24
74	80	52	99	178	1784	1110	21	64	81	568	880	681	463	401	241	201	515	330	463	398	18	15
76	29	20	0	25	127	777	1	18	2	47	176	182	234	249	76	79	36	53	76	161	3	6
78	3	8	0	0	0	40	0	0	0	6	4	23	2	33	7	11	5	4	2	14	0	1
80	1	0	0	0	0	3	0	0	0	0	0	0	0	3	0	10	0	3	0	2	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		Sum:	2628	2629	100	100

Table 4. Cooling season temperature difference between the attic and the thermostat location.

Attic-tstat temperature		Fr coo			% of						
difference bins	476	1698	1818	1826	1927	1974	2245	2300	2356	Average	samples
-6	0	0	0	0	0	0	0	0	0	0	0
-4	0	0	1	0	0	0	0	0	0	0	0
-2	150	25	12	11	38	19	19	82	115	52	3
0	930	519	735	578	709	693	693	790	645	699	36
2	363	456	487	540	427	430	430	378	267	420	22
4	387	630	508	600	421	442	442	400	294	458	24
6	146	280	229	237	312	280	280	271	198	248	13
8	7	61	7	6	49	100	100	58	41	48	2
10	0	1	0	0	0	8	8	2	0	2	0
12	0	0	0	0	0	0	0	0	0	0	0
									Sum:	1927	100

Table 5. Heating season temperature difference between the attic and the thermostat location.

Attic-tstat temperature			quency			% of					
difference bins	476	1698	1818	1826	1927	1974	2245	2300	2356	Average	samples
-6	0	0	0	0	0	0	0	0	0	0	0
-4	0	5	0	0	1	0	0	0	27	4	0
-2	754	324	147	51	227	190	190	438	761	342	13
0	1863	1545	1129	1718	1187	1976	1976	1794	1721	1657	63
2	173	617	1207	681	808	353	353	298	267	529	20
4	5	63	307	81	312	18	18	24	19	94	4
6	0	0	4	5	1	0	0	0	0	1	0
8	0	0	0	0	0	0	0	0	0	0	0
									Sum:	2626	100

fan installed in an exterior door, in such a way that the pressure differential across the ceiling was brought to zero (nulled). With the house and the attic at $-50\,\mathrm{Pa}$ with respect to outside, the flow through the fan mounted in the attic access should theoretically represent the attic leakage to outdoors. The attic nulled-test was labor-intensive and did not show consistency in providing a qualification criterion that was coherent relative to the other tests.

The measured temperature conditions showed that the UC attics were essentially at the same conditions as the actively conditioned space.

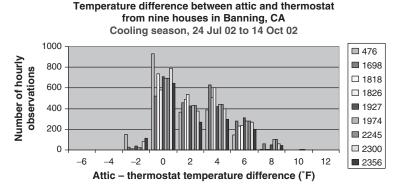


Figure 1. Summary of cooling season temperature difference between the UC attic and the thermostat location for nine houses in Banning, CA.

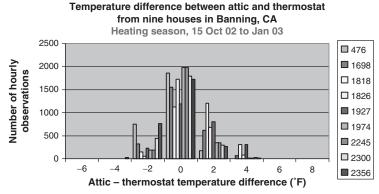


Figure 2. Summary of heating season temperature difference between the UC attic and the thermostat location for nine houses in Banning. CA.

This did not change with variation in the leakage and pressure differential test results. Hence, the current opinion is that the UC attic space behaves nearly the same as the actively conditioned space below it when it meets the leakage criteria for building enclosure with the attic access open. The cfm50 test with the attic access open is easy to perform and seems to provide the best qualification.

Additional Temperature and Relative Humidity Monitoring Near Phoenix, AZ

Four houses with UC attics were monitored for temperature and RH conditions north of Phoenix, AZ. Data for a representative house are shown

Table 6. Building enclosure air leakage, pressure differential, and pressure-nulled attic airflow measurements for 33 houses in California and Arizona.

House ID	Specified maximum building leakage (cfm50)	Building leakage with attic access open (cfm50)	Pass/fail leakage criteria (%)	Building leakage with attic access closed (cfm50)	Difference open-closed (%)	House to attic dP with house at -50 Pa (Pa)	Attic leakage with ceiling nulled out (cfm50)
1	1270	816	36	785	4	10	294
10	1753	1156	34	999	14	16	378
24	2200	1500	32	1140	24	22	1050
26	2150	1472	32	1207	18	23	504
30	2200	1545	30	1146	26	25	756
19	2390	1690	29	1325	22	18	1160
4	1410	1102	22	985	11	13	811
6	1410	1106	22	907	18	15	787
13	1410	1124	20	929	17	17	806
14	1410	1180	16	966	18	17	832
9	1610	1350	16	1206	11	16	921
12	1410	1216	14	950	22	17	810
7	1950	1690	13	1531	9	16	1075

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5	1410	1226	13	1066	13	13	846
25	2010	1820	9	1380	24	22	1289
8	1750	1600	9	1406	12	16	1050
3	1320	1208	8	1063	12	12	504
23	1410	1296	8	976	25	21	1039
21	2010	1860	7	1414	24	21	1295
17	2200	2050	7	1680	18	18	1284
15	2390	2259	5	1809	20	17	1310
11	1810	1729	4	1449	16	16	1075
33	1650	1580	4	1267	20	27	819
18	1750	1690	3	1560	8	18	1090
28	1800	1741	3	1314	25	24	504
20	1750	1720	2	1380	20	19	1004
16	1410	1458	-3	1176	19	18	1045
22	1410	1510	-7	1093	28	21	1289
29	1520	1657	-9	1290	22	24	630
27	1750	1920	-10	1660	14	24	1078
2	1950	2340	-20	2225	5	11	790
31	1410	1726	-22	1275	26	25	1242
32	1410	1738	-23	1254	28	26	1304

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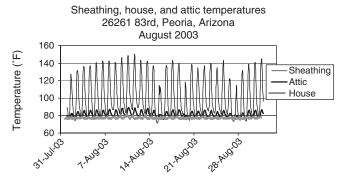


Figure 3. Hourly temperatures at the bottom of roof sheathing, in the UC attic space, and in the actively conditioned space for a house near Phoenix, AZ for the month of August.

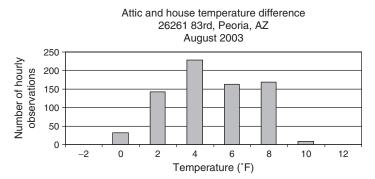


Figure 4. Frequency plot of temperature difference between the UC attic space and the actively conditioned space for a house near Phoenix, AZ for the month of August.

in Figures 3 and 4 for the month of August, which represents the hottest and the most humid conditions. The roof sheathing temperature reached a peak of 150°F (65.6°C), while at the same time, the house was conditioned to a steady 78°F (25.6°C) and the UC attic was at most 10°F (about 6°C) warmer than the actively conditioned space. This measurement was with no intentional supply of air in the UC attic. The UC attic was only 4°F (2°C) warmer than the actively conditioned space for the greatest number of hours. Four days of overcast conditions were observed in the data when the sheathing temperature was significantly lower and the attic and house temperatures were nearly the same.

Relative humidity (RH) conditions in the actively conditioned space show that the UC attic and the sheathing-insulation interface centered around 32% RH. The daily swings ranged between 28 and 35% in the actively

conditioned space, between 26 and 40% for the UC attic, and between 24 and 45% for the sheathing–insulation interface. None of these conditions presented any concern. Relative humidity was about the same between the actively conditioned space and the UC attic for the majority of hours, within the range of measurement uncertainty.

COLD CLIMATE

If air permeable insulation is used for UC attics in climates with roof sheathing temperatures that dip below $45^{\circ}F$ ($7^{\circ}C$) for days at a time, then rigid insulation should be installed above the structural roof sheathing to keep the roof sheathing temperature above $45^{\circ}F$ ($7^{\circ}C$) (dew point for interior conditions of about $70^{\circ}F$ ($21^{\circ}C$) dry bulb and $40^{\circ}M$ RH).

Observations in Minnesota, Wisconsin, and Massachusetts

A field investigation of four sites was conducted in Minnesota and Wisconsin on 5–6 April 2004, and at one site in Massachusetts on 9 March 2004. That time of the year was chosen to conduct the inspection since any potential moisture accumulation at the sheathing–insulation interface should be most evident then. An open-cell, semi-flexible, low density foam with a published water vapor permeance of 16 imperial perm (915 ng/(Pa-s-m²)) at 3-in. thickness (≈75 mm) was used in this building.

At all the sites investigated, at least one sample of the foam insulation was removed from within 5 ft (1.5 m) of the roof peak. The location near the roof peak was chosen to reflect the worst case, since indoor air moisture conditions are most elevated at high points in roofs due to moisture buoyancy. Where possible, samples were taken from multiple cardinal orientations, but especially the north and south facing directions, since they represent the coldest and warmest roof surfaces, respectively, due to solar exposure.

Immediately after removal of the insulation, visual and physical observations of the roof sheathing were made to determine the presence of any bulk moisture, mold, wood discoloration, rot, wood deterioration, or delamination. Measurements were made to determine the wood moisture content of the roof sheathing and of the surrounding framing materials as a reference. The moisture meter used was a digital, pin-type meter made by Delmhorst, calibrated for spruce—pine—fir (SPF) wood. While probing the roof sheathing with the moisture meter pins, any indication of wood softness was also noted.

The tabulated results are shown in Table 7. There was a significant amount of solar-induced drying on southern exposures where the sheathing

Table 7. Moisture measurement and observation results.

Location	HDD (65°F)	House ID	Mo/Yr insulated	Sample ID	Foam insulation type	Insulation thickness (in.)		Roofing type	Roof orientation (N,E,S,W)	House RH (%)	Attic RH (%)	Attic T (°C)	Sheathing moisture content range (%)	Framing moisture content range (%)
Minnesota														
Duluth	9906	MN1	Nov-01	MN1a	Open-cell	4–6	Plywood	Comp shingle	S, mid	44	70	68	12-17	11–12
				MN1b	Open-cell	3–5	Plywood	Comp shingle	N, mid	44	70	68	>40	11–12
				MN1c	Open-cell	5–8	Plywood	Comp shingle	N, east	44	70	68	>40	11-12
				MN1d	Open-cell	5–7	Plywood	Comp shingle	S, east	44	70	68	12–16	11–12
Duluth	9906	MN2	Nov-01	MN2a	Open-cell	4–7	Old boards	Comp shingle	N, west		40-50	70–78	26–31	9–10
				MN2b	Open-cell	4–7	Old boards	Comp shingle	S, west		40-50	70-78	7–10	9–10
				MN2c	Open-cell	4–7	Old boards	Comp shingle	N, east		40-50	70-78	25-28	9-10
				MN2d	Open-cell	4–7	Old boards	Comp shingle	S, east		40-50	70-78	8–9	9–10
				MN2e	Open-cell	4–7	Old boards	Comp shinale	N. mid		40-50	70-78	27-30	9–10

Kelsey	9906	MN3	??-02	MN3a MN3b	Open-cell Open-cell	4–7 3–7	OSB OSB	Comp shingle Comp shingle	N, west S, east		30 30	72 72	20–25 16–19	7–8 7–8
Duluth area	9906	MN5	??-02	MN5a	Closed-cell	3	OSB	Comp shingle	N		30	73	6–7	<6
Wisconsin														
Danbury	9061	MN4	??-01	MN4a	Open-cell	6–9	OSB	Comp shingle	W, north	53	>85	71	>40	6–8
				MN4b	Open-cell	6–9	OSB	Comp shingle	E, north	53	>85	71	>40	6–8
				MN4c	Open-cell	6–9	OSB	Comp shingle	S (gable wall)	53	75	71	21-23	
				MN4d	Open-cell	6–9	OSB	Comp shingle	E, mid, low	53	64	71	25-38	
				MN4e	Open-cell	5.5	OSB	Wood siding	E (high wall)	53		71	24-33	
				MN4f	Open-cell	5.5	OSB	Wood siding	W (mid wall)	53		71	25–30	
Massachus	etts													
Somerville	5596	MA1	??-03	MA1a	Open-cell	6–8	Old boards	Slate	E, north	30	30	68	16-18	10-12
				MA1b	Open-cell	6–8	Old boards	Slate	W, north	30	30	68	12-15	10-12
				MA1c	Open-cell	6–8	Old boards	Slate	E, south	30	30	68	13-17	10-12
				MA1d	Open-cell	6–8	Old boards	Slate	W, south	30	30	68	11-13	10-12

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moisture content was generally much lower than on northern exposures. There was less of a difference between east and west orientations, but, generally, west exposures were drier than east exposures and both were drier than north exposures.

In some cases shown in Table 7, indoor humidity was higher than normal. For instance, the house at MN1 experienced a flooded basement floor about a week before the inspection (about 1 in. of water). The basement was simply left to dry up through the house, causing very high humidity conditions in the UC attic. The house at MN2 was originally built over a basement which was later filled in because of constant flooding. The house at MN4 was a lake house (cottage), infrequently occupied, and in an unfinished state with exposed open-cell foam on the roof and most of the walls. However, the owner was found to have been humidifying the space to 50% RH. The house had no operating ventilation system.

Considering the severe cold climate, the high humidity conditions, and the permeable open-cell foam insulation, it is understandable that unsatisfactory wood moisture conditions were found at three out of the four houses inspected in Minnesota and Wisconsin. Despite this, there were no observations of fungal growth or wood deterioration.

HOT-HUMID CLIMATE

New lessons were learned in the hot-humid climate application of UC attics in tract construction which had asphalt composition shingles. Until recently, the roofing industry feared that insulated roofs allowed the buildup of higher temperatures and that this would cause premature deterioration of shingles.

Houston, TX

A project in Houston, TX, used netted and blown-in cellulose insulation under the roof sheathing. Monitoring of temperature and humidity conditions above and below the insulation showed interesting and different results compared to hot—dry climate applications with tile roofs. It became apparent that solar-driven moisture through composition shingles was a significant factor to be accounted for. When roof temperatures fall below the dew point because of the night sky radiation, moisture condenses on the top surface of the roof. Thus, in the morning, the roofs are generally wet. Some of this moisture is drawn into the material and between the laps of shingles. Solar radiation subsequently heats the roof surface and drives water vapor into the roof assembly. Observations of elevated humidity

conditions were coincident with the morning heating of the roof surface, as shown in Figure 5.

The solar-powered vapor drive peaks at about noontime, after which the shingles are dry and the moisture distribution follows the thermal gradient toward the interior space. Notice that the signal is muted when there is rain or little sunshine as especially evident in Figure 6. Some of the moisture is driven all the way through the insulated roof assembly and is removed by the space conditioning system. Some of the moisture is stored in the insulation – more so for cellulose than fiberglass. In addition, there appears

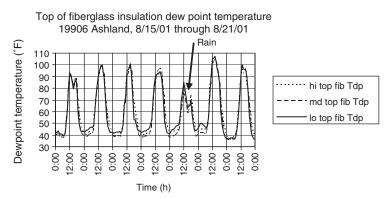


Figure 5. Observations of elevated humidity conditions are coincident with the morning heating of the roof surface, measured on top of the insulation at three heights in the cathedralized attic.

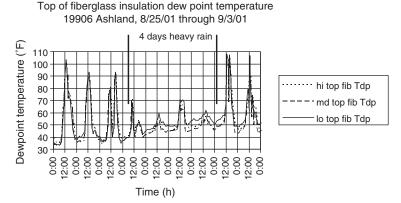


Figure 6. Even though the roof is wet, lack of sunshine during rain or overcast conditions mutes the water vapor drive into the roof assembly.

to be migration of moisture up to the highest points in the attic due to moisture buoyancy and air movement due to thermal buoyancy. Where hip or valley rafters, ridge boards, or roof peaks exist, the moisture tended to concentrate there as evidenced by some observations of elevated wood moisture and rusted fasteners. However, the measured data showed elevated dew points with increasing height only during daytime. This indicates that moisture removal by the space conditioning system was sufficient to equalize humidity conditions to that of the actively conditioned living space each night. While the space conditioning system (cooling plus dehumidification) can remove this moisture, it is prudent to eliminate the moisture load by installing a vapor retarding roof underlayment beneath the composition shingles. Such roof underlayment should be used instead of traditional #15lb felt roofing paper, which has a water vapor transmission of about 6 imperial perm (343 ng/(Pa-s-m²)). Vapor retarding roof underlayment is commercially available with water vapor transmission of less than 1 imperial perm (57.2 ng/m² s Pa). The material costs about 3-4 times that of #15 lb felt.

For the particular house discussed here, in Figures 5 through 8, two roof bays – one insulated with R-22 netted, dense-pack cellulose and the other one with R-30 unfaced fiberglass batts, were instrumented with temperature and RH sensors. The sensors were placed in pairs above (top) and below (bot) the insulation, near the peak (hi), in the middle (md), and near the eave (lo). The approximately 18 ft (5.5 m) long, 8/12 pitch sloped roof faced south.

Hourly dry bulb temperature measurements taken between the roof sheathing and the insulation show the wide temperature swing between the morning (150–170°F (65–76°C)) and night hours (70°F (21°C)). Relative humidity at the interface between the top of the insulation and the roof sheathing stayed low, while RH at the bottom of the insulation (also representative of the attic air space at that height) was higher, with daily pulses near saturation close to the roof peak. Interestingly, the moisture storage capacity of the cellulose insulation, shown in Figure 7, moderated the near saturation moisture pulse observed where fiberglass insulation was used (Figure 8).

Jacksonville, FL

In Jacksonville, FL a UC attic house was directly compared to a similar house with a vented attic. The temperature on the asphalt fiberglass-reinforced shingles was measured. For the entire month of August 2001, the peak shingle temperature was 180°F (82°C) and the peak shingle

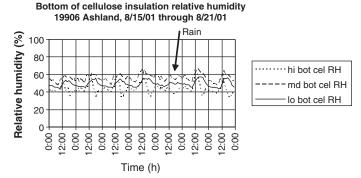


Figure 7. Hourly RH at the bottom of the R-22 cellulose insulation, showing how the moisture storage capacity of the cellulose dampens the moisture pulse through the assembly.

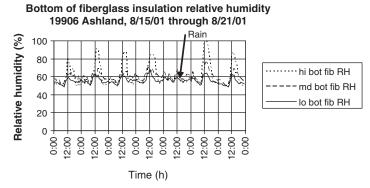


Figure 8. Hourly RH at the bottom of the cathedralized R-30 fiberglass insulation, showing the elevated level, especially near the peak, as the roof moisture moves through the assembly.

temperature difference was 7°F (about 4°C). On average over the whole month, the UC attic shingles were 0.2°F warmer than those over the standard vented attic. These data represent the worst case – dark, gray-black, south-facing shingles.

For comparison, Cash and Lyon (2002) previously reported a calculated annual average shingle temperature increase of 0.9°F (0.5°C) for vented versus unvented attics in Miami. Parker and Sherwin (1998) previously reported a measured peak shingle temperature increase of 5°F (2.8°C) due to a radiant barrier system.

Figure 9 also illustrates the roof temperature depression, due to night sky radiation, which lowered the roof temperature below the ambient air

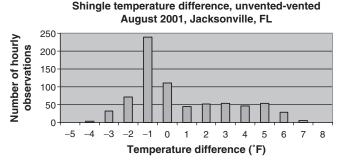


Figure 9. Histogram of roof shingle temperature difference over vented and UC attics in Jacksonville. FL.

dew point temperature and caused condensation on the roof shingles. Air temperature stratification in both the UC attic and the vented attic was nearly identical even though the actual temperatures were quite different. The maximum air temperature difference between the high attic and low attic was 12°F (6.7°C), while the high attic was only 3°F (1.7°C) warmer than the low attic on average.

In winter, if the roof sheathing temperature falls below the UC attic air dew point temperature for long periods, condensation can occur on the bottom of the roof sheathing. This was observed near roof peaks in both Houston, TX and Jacksonville, FL with cellulose and fiberglass insulation, but not with the open-cell foam. The open-cell foam is permeable to water vapor (10 imperial perm at 5 in. thickness (572 metric perm at 13 cm thickness)), but provides somewhat higher resistance to airflow. Figure 10 shows wintertime roof sheathing temperature, for the worst-case north orientation, along with the cathedralized attic air dew point temperature. The north orientation received the least solar heat, hence, the temperature remained cooler and the drying potential was lower.

Lake City, FL

In February 2003, roof sheathing inspections were conducted at two houses in northern Florida to evaluate potential moisture accumulation. That time of the year was specifically chosen to conduct the inspection since any potential moisture accumulation at the plywood–insulation interface would have been most evident at the end of a winter season. Both houses had open-cell, low-density foam insulation sprayed under the plywood roof sheathing, creating a sealed (non-vented) attic. The roofing material over the roof sheathing was #15 lb roofing felt and asphalt/fiberglass shingles.

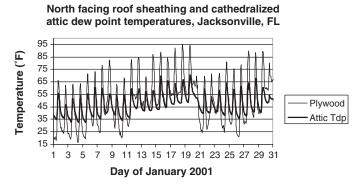


Figure 10. Hourly measurements of roof sheathing temperature and UC attic dew point temperature in Jacksonville, FL.

Wood moisture content measurements of the roof sheathing and the surrounding roof framing were made, as well as visual and physical observations of the conditions of the roof sheathing. One temperature and relative humidity sensor was installed at each house between the roof sheathing and the foam insulation. These monitors will record temperature and RH every 4h for up to 2 years.

At the time of inspection, the roof sheathing showed no signs of moisture condensation, mold, discoloration, delamination, or deterioration. The roof sheathing, and adjacent framing, appeared as good as new. Wood moisture content readings ranged between 7 and 16% for the sheathing with the median about 10%. The surrounding framing ranged from 7 to 12% with the median about 9%.

CONCLUSIONS

Several monitoring and field testing studies were conducted to quantify the performance of the UC attic approach. Measured results showed that UC attic spaces operate near the conditions of the living space. Use of insulation that restricts convective air movement was found to control condensation at the underside of the roof sheathing. It has been shown that increased vapor diffusion resistance is needed beneath asphalt roofing materials to control solar-driven moisture ingress. The summertime average daily temperature of roofing materials is nearly unchanged whether vented or unvented, while short-term peak temperature increases are not more

than 7°F. Since the temperature of the roof shingles was shown not to be significantly affected by the presence of insulation it was unlikely to affect the durability of the shingles. These increases are similar to the peak effect of radiant barriers. If air permeable insulation is used, rigid insulation must be placed above the structural roof sheathing with specific exceptions. ¹

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¹Exceptions include IECC zones 1, 2B, and 3B except Texas.

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