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Unvented-Cathedralized, Conditioned Attics: A Comprehensive Update

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ABSTRACT

The unvented-cathedralized attic approach involves moving the air pressure boundary and thermal insulation boundary from the living space ceiling to the plane of the roof, for which the main purpose is to enclose thermal air distribution systems within conditioned space to increase efficiency, comfort, indoor air quality, durability, and maintainability. The insulation may be air impermeable or air permeable, and the roof assemblies may have varying degrees of vapor diffusion resistance, but specific design criteria should be considered. Measured data is presented by climatic region concerning temperature increase of asphalt shingles, temperature and moisture conditions of unvented-cathedralized attic spaces and roof sheathing, and air leakage rates. Activities and progress relating to building and energy code approval are discussed.

INTRODUCTION

The unvented-cathedralized attic approach involves moving the air pressure boundary and thermal insulation boundary from the living space ceiling to the plane of the roof and gable end walls if applicable (Rose 1995). In doing so, an attic mounted space conditioning air distribution system is then inside conditioned space, eliminating direct loss to outside. An unvented-cathedralized attic differs from a cathedral ceiling, whether vented or unvented, in that the cathedral ceiling has interior finish materials installed beneath the roof framing and insulation, whereas, the insulation and framing are left exposed in the unvented-cathedralized application.

The earliest form used in residential construction was by application of expanding spray foam insulation directly adhered 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 due to condensation of moist outdoor air on cool supply air ducts or gypsum wallboard surfaces (Lstiburek 1993). While the extra expense of correcting a moisture problem can be easily justified, it is often much harder to sell a premium option for the more price sensitive new construction market. Hence, less expensive methods of cathedralizing have been used extensively, such as netted-and-blown cellulose, and strapped-in-place fiberglass batts. The spray foam application inherently eliminates air movement, whereas the fibrous insulation application allows air movement which can cause moisture condensation on roof sheathing depending on the sheathing temperature. Proper design must be applied to avoid long-term moisture condensation. Of the three materials, the easiest way to provide high insulation R-value at uniform thickness is fiberglass batts. Spray foam is generally less uniform in thickness than fiberglass batts but more uniform than netted cellulose due to netting that droops between more shallow framing members. Although it can be thicker, spray foam is generally not applied at R-values higher than 20 Btu/h-ft^2-°F whether the foam is high density (1.5 to 2 lb/ft^3) or low density (0.5 lb/ft^3). Spray foam applicators generally consider R-20 to be an optimum level, especially considering the air sealing capability and air impermeable nature of the material. Likewise, as a value point rather than a limitation, cathedralized netted cellulose insulation is generally installed densely packed to an effective R-value of 22 Btu/h-ft^2-°F.

Properly applied, the unvented-cathedralized 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 air pressure boundary of the conditioned space. This has been shown to provide substantial benefit in both summer and winter (Rudd et al. 2000, Hendron et al. 2003, Hedrick 2003). It is more energy efficient secondarily because, with many ceiling penetrations and height changes, it is often easier to air seal the building enclosure at the roof 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.

Supporting research for the unvented-cathedralized attic approach started with 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 caused 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.

NEW OBSERVATIONS BY CLIMATE REGION

Hot-Dry and Mixed-Dry Climate

With support from simulations and data monitoring, it was desirable to provide a body of information to facilitate broad code approval without having to continue to convince code officials on a jurisdiction-by-jurisdiction basis. For example, an important hurdle in California and parts of Arizona was to be able to claim the benefit of having the thermal air distribution ducts inside conditioned space without having to actively condition the unvented-cathedralized attic.

For dwellings with an unvented-cathedralized attic, the ceiling gypsum board plane is not purposefully constructed to be airtight as it would be for houses with a vented attic. Therefore, there is natural air exchange between the living space and the unvented-cathedralized 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.

Data was collected and analyzed to provide justification to demonstrate that the thermal air distribution system, located inside the unvented-cathedralized attic, was for all intents and purposes inside conditioned space. A two-faceted approach was taken:

1) To provide evidence that, by using the unvented-cathedralized attic approach, the average and peak temperature difference between the living space and the attic is small, therefore, this indirectly conditioned space should be considered the same as a conditioned space for the purpose of energy performance; and

2) To provide practical measurement criteria by which the unvented-cathedralized attic could be qualified as being acceptably tight with low air leakage to outdoors.

Temperature measurements can demonstrate where the effective thermal insulation boundary is. 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, pressure differential and air leakage measurements can demonstrate where the primary air pressure boundary is. 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.

A combination of pressure differential and air leakage measurements could create a set of criteria to bound the acceptability of a given unvented-cathedralized attic construction as one that would provide the predicted performance as indicated by the measured temperature conditions in the attic versus the living space.

Measurement of pressure differential, building enclosure air leakage, and hourly monitoring of attic versus living space temperature and relative humidity conditions were made between late July 2002 and January 2003 for ten unvented-cathedralized attic houses in Banning, California.

<u>Pressure differential and building enclosure air leakage</u>

Pressure differential was measured across the ceiling between the attic and living space, with the attic access closed and the living space depressurized to –50 Pa with respect to outside. If the attic was perfectly sealed to outside, and the ceiling was sufficiently leaky, the pressure differential across the ceiling would be zero. If the attic was leaky to outside, the pressure differential would tend toward 50 Pa across the ceiling.

Total building enclosure leakage at -50 Pa pressure differential with respect to outside was 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).

Measured results are listed in Table 1 for 10 houses constructed by the same builder in California. The pressure differential ranged between a low of 10.6 and a high of 19.0, with the average being 15.7 Pa. This means that, on average, the roof plane was about 70% of the total roof air pressure boundary and that the ceiling gypsum board was about 30%.

Based on the data in Table 1, a criteria for acceptably tight conditioned attics was postulated as less than 20% difference between the attic access open and closed tests and less than 17 Pa pressure difference across the ceiling with the house at –50 Pa. However, in a later study of 33 houses constructed by different builders in other locations in California and Arizona, it became apparent that unpredictable differences in ceiling air tightness made it unreasonable to use the pressure differential measurement as an attic air tightness qualifying criteria. The ceiling plane air tightness varied too much due to the number of recessed canister lights and other ceiling penetrations, chases, soffits, and coffers. This data is shown in Table 2; the records were sorted in descending order with those that passed the building leakage test by the largest margin first. 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 where a calibrated fan was installed in the attic access in addition to the calibrated fan installed in an exterior door, such that, the pressure differential across the ceiling was nulled. With the house and the attic at –50 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 nulling test was labor intensive and did not show consistency in providing a qualification criteria that was coherent relative to the other tests.

The measured temperature conditions showed that the unvented-cathedralized attics were essentially at the same conditions as the actively conditioned space. This did not change with variation in the leakage and pressure differential test results. Hence, the current thinking is that the unvented-cathedralized attic space behaves nearly the same as the actively conditioned space below it when it meets a relatively tight building enclosure leakage criteria with the attic access open,. The attic-access-open cfm50 test is easy to perform and seems to provide the best qualification criteria.

Table 1 Building enclosure air leakage and pressure difference measurements for ten houses in Banning, California

Address	cfm50 attic access open (ft^3/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

Table 2 Building enclosure air leakage, pressure differential, and pressure-nulled attic air flow measurements for 33 houses in California and Arizona

House ID	Specified max bldg 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
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

Attic and living space temperature conditions

Data loggers recording hourly temperature and relative humidity were installed 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 feet from the attic floor.

Summary analysis for nine of the ten houses is given in Tables 3 thru 6 and Figures 1 thru 3. The owners of the tenth house declined involvement part way through the monitoring period. Outdoor air temperature is given in Figure 3, ranging up to 102° F during the cooling season and down to 32° F during the heating season.

In Table 3, the most common temperature bin, both at the thermostat and in the attic, was between 74 and 76° F during the cooling season portion of the monitoring (24-Jul-02 thru 14-Oct-03). In Table 4, the most common temperature bin, both at the thermostat and in the attic, was between 70 and 72° F during the heating season portion of the monitoring (15-Oct-02 thru Jan-03).

In Table 5 and Figure 1, most of the hourly temperature samples show that, during the cooling season portion of the monitoring, the attic was between –2 and +6 degrees F of the living space, with the largest group between –2 and 0 degrees temperature difference. In Table 6 and Figure 2, during the heating season, the attic was mostly between –2 and +2 degrees of the living space, with the largest group between –2 and 0 degrees temperature difference.

Table 3 Cooling season temperatures at the thermostat location and in the attic

Frequency of houry observations during COOLING season
24-JUL-02 through 14-OCT-03

Air Temperature bins (F)	476		1698		1818		1826		1927		1974		2245		2300		2356		Average		% of samples	
	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	tstat	attic	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 4 Heating season temperatures at the thermostat location and in the attic

Frequency of houry observations during HEATING season
15-OCT-02 through JAN-03

Air Temperature bins (F)	476		1698		1818		1826		1927		1974		2245		2300		2356		Average		% of samples	
	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 5 Cooling season temperature difference between the attic and the thermostat location

Attic - Tstat Temperature Difference bins	Frequency of hourly observations during COOLING season 24-JUL-02 through 14-OCT-03										
	476	1698	1818	1826	1927	1974	2245	2300	2356	Average	% of 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 6 Heating season temperature difference between the attic and the thermostat location

Attic - Tstat Temperature Difference bins	Frequency of hourly observations during HEATING season 15-OCT-02 through JAN-03										
	476	1698	1818	1826	1927	1974	2245	2300	2356	Average	% of 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%

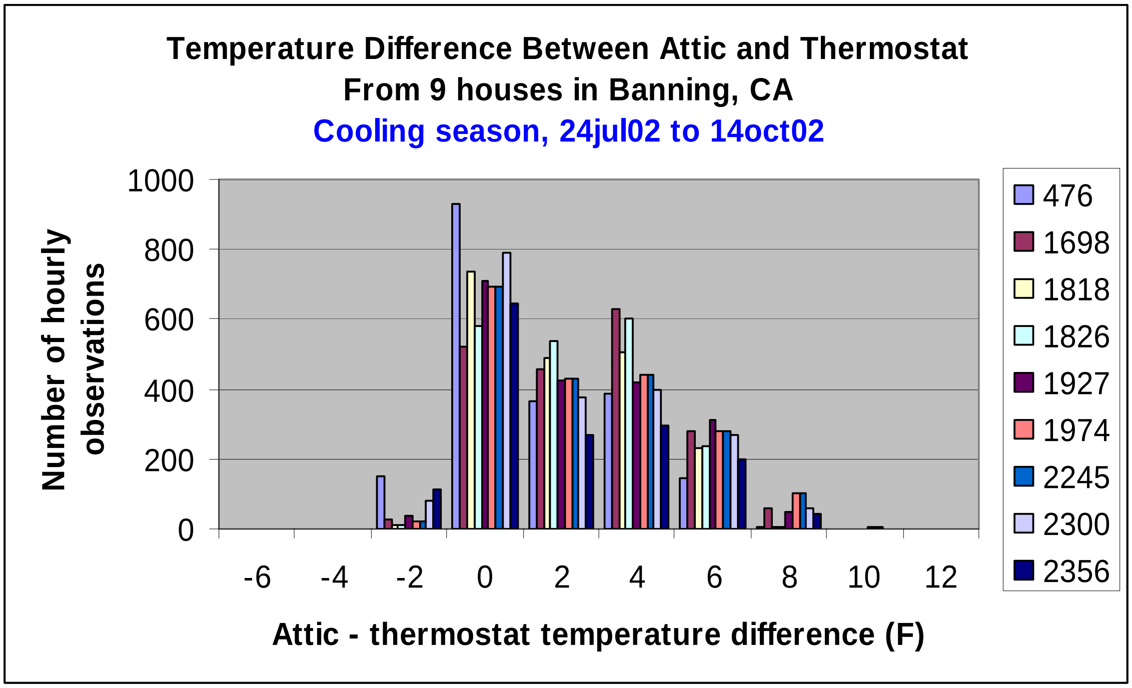

Figure 1 Summary of cooling season temperature difference between the unvented-cathedralized attic and the thermostat location for 9 houses in Banning, CA

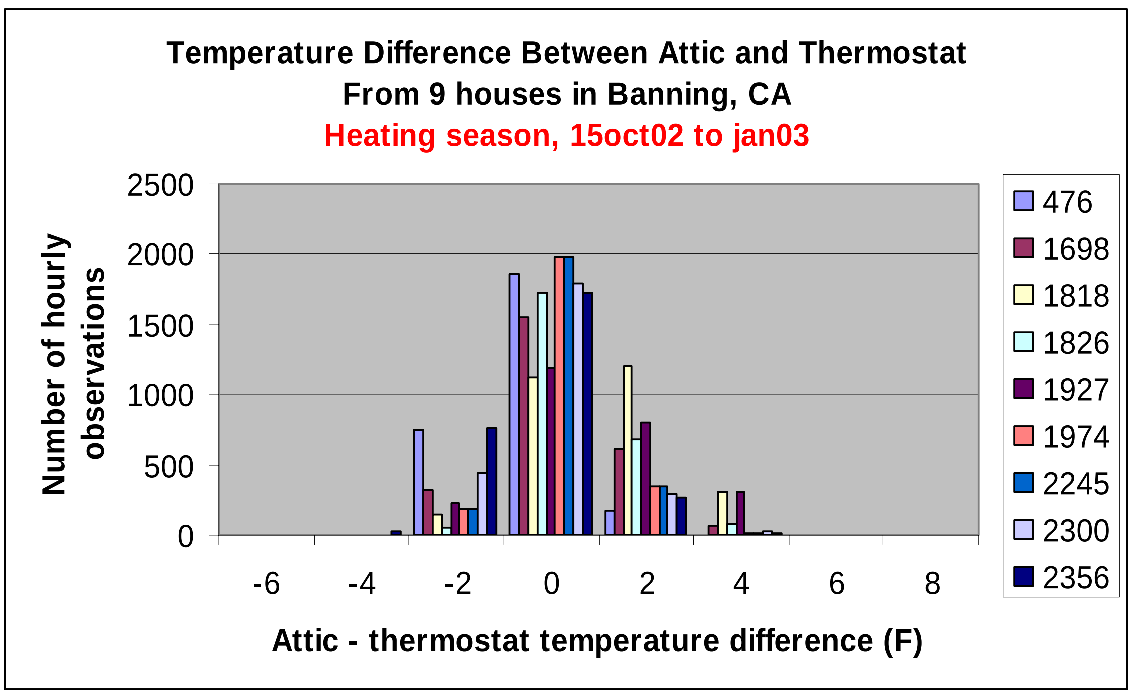

Figure 2 Summary of heating season temperature difference between the unvented-cathedralized attic and the thermostat location for 9 houses in Banning, CA

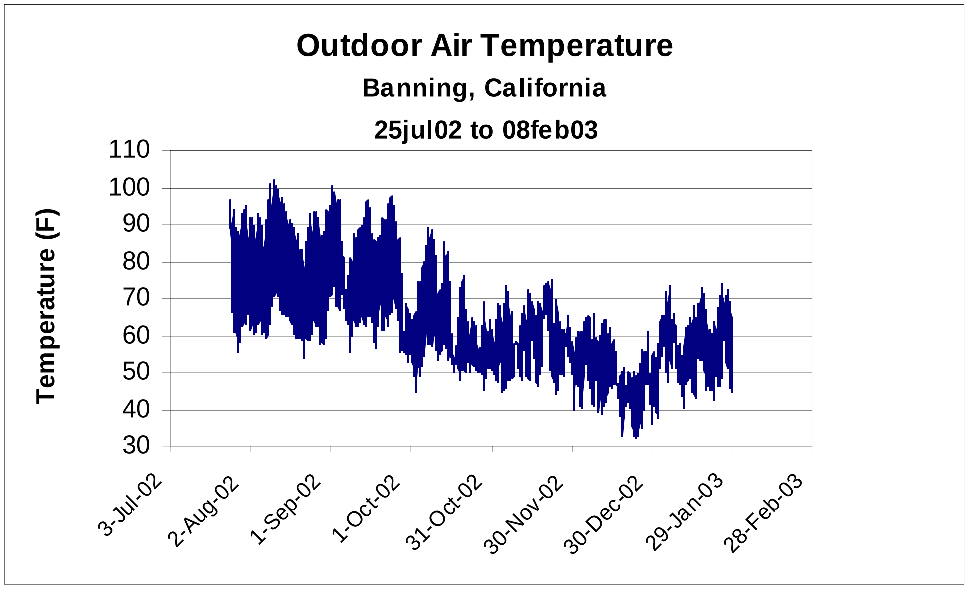

Figure 3 Hourly outdoor air temperature during monitoring period in Banning, CA

Figure 4 Banning, CA test houses

Figure 5 Peoria, AZ test house

Additional temperature and relative humidity monitoring near Phoenix, AZ

Four houses with unvented-cathedralized attics were monitored for temperature and relative humidity conditions north of Phoenix, Arizona. Data are shown in Figures 6 through 8 for a representative house for the month of August, which represents the hottest and most humid (monsoon season) conditions. The roof sheathing temperature reached a peak of 150° F, while at the same time, the house was conditioned to a steady 78°F and the cathedralized attic was at most 10° F warmer than the actively conditioned space. This was with no intentional supply air in the cathedralized attic. As shown in Figure 8, the cathedralized attic was only 4° F warmer than the actively conditioned space for the greatest number of hours. Four days of overcast conditions can be observed in the data where the sheathing temperature was significantly lower and the attic and house temperatures were nearly the same.

Referring to Figure 7, relative humidity (RH) conditions in the actively conditioned space, that cathedralized 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 cathedralized attic, and between 24% and 45% for the sheathing-insulation interface. None of these conditions presented any concern. Based on the frequency plot in Figure 9, relative humidity was about the same between the actively conditioned space and the cathedralized attic for the majority of hours, within the range of measurement uncertainty.

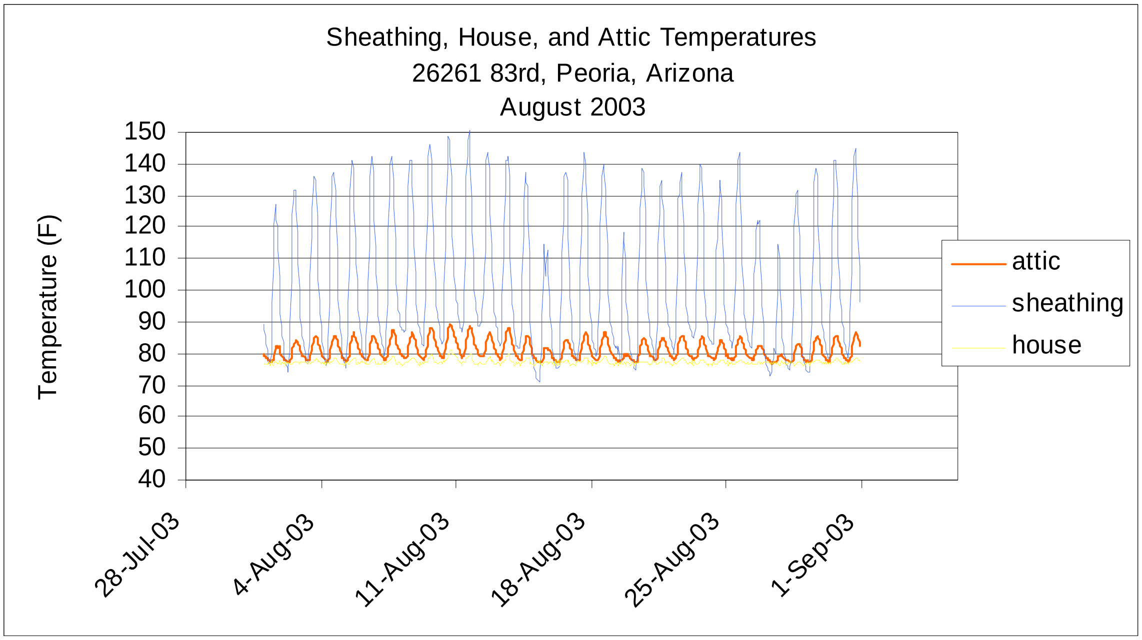

Figure 6 Hourly measured temperature at the bottom of roof sheathing, in the unvented-cathedralized attic space, and in the actively conditioned space for a house near Phoenix, AZ for the month of August

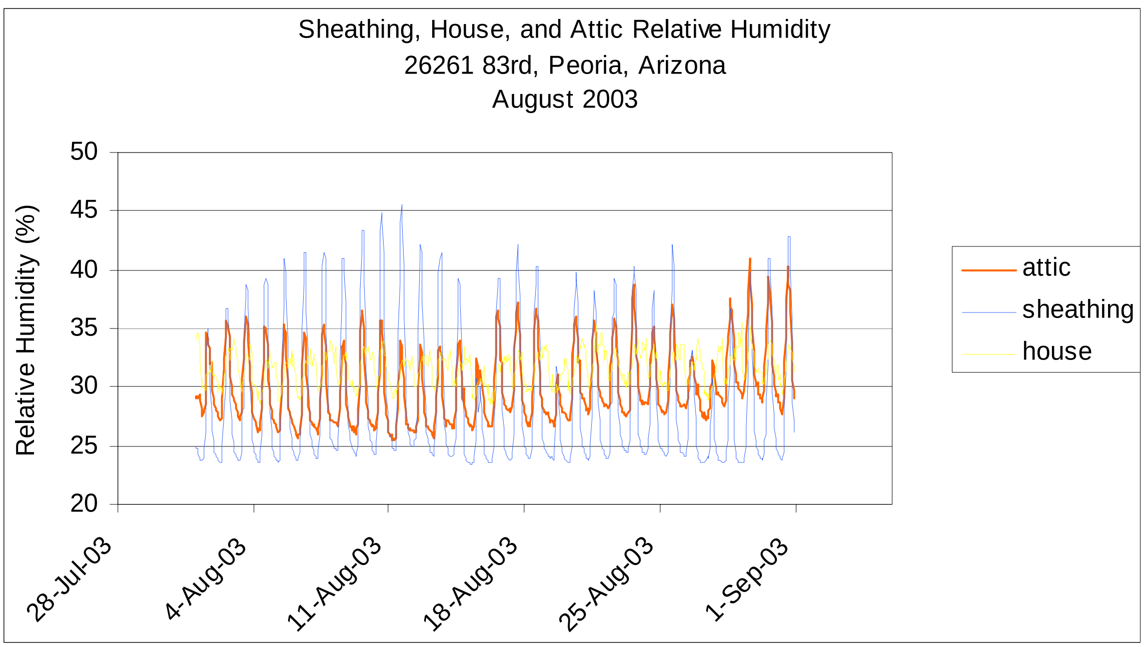

Figure 7 Hourly measured relative humidity at the bottom of roof sheathing, in the unvented-cathedralized attic space, and in the actively conditioned space for a house near Phoenix, AZ for the month of August

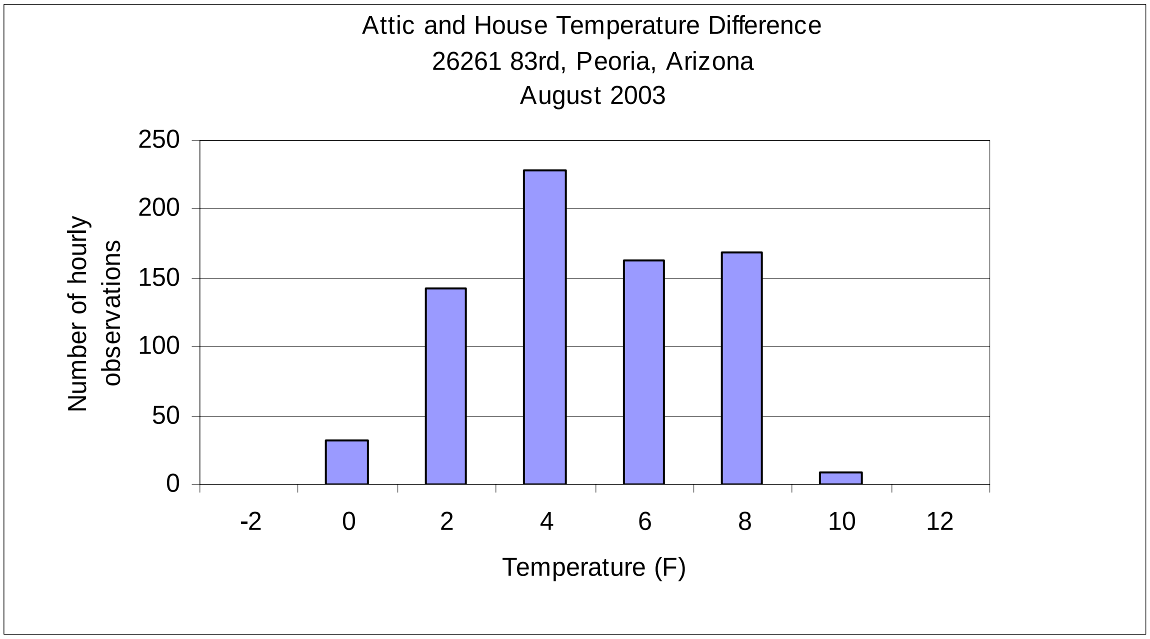

Figure 8 Frequency plot of temperature difference between the unvented-cathedralized attic space and the actively conditioned space for a house near Phoenix, AZ for the month of August

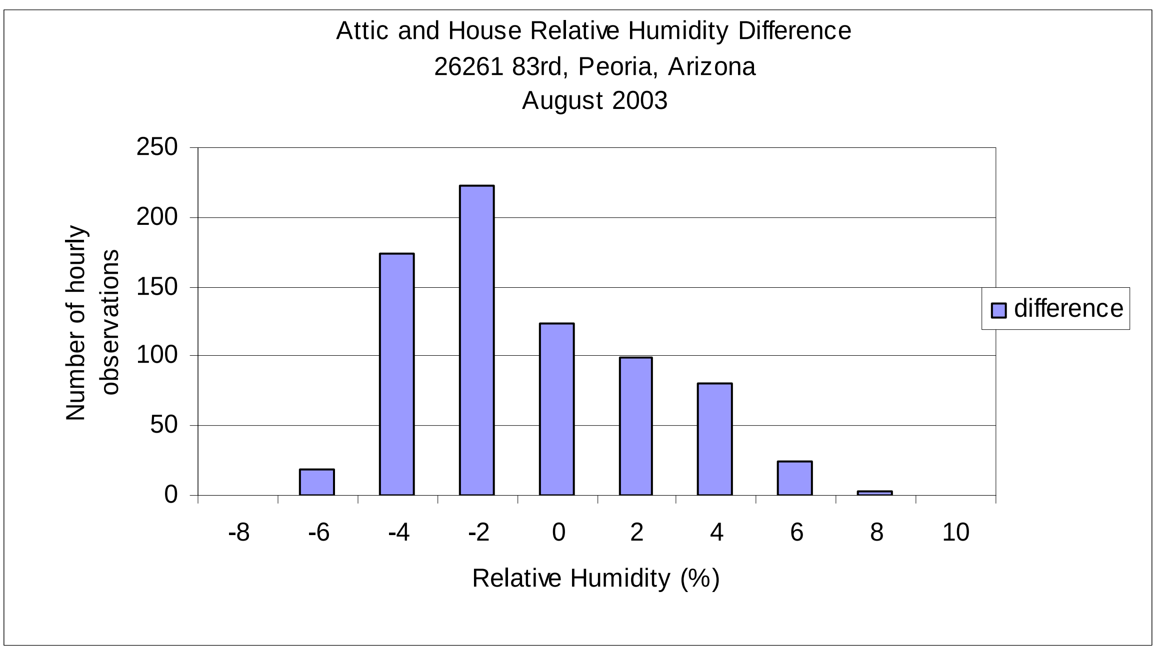

Figure 9 Frequency plot of relative humidity difference between the unvented-cathedralized attic space and the actively conditioned space for a house near Phoenix, AZ for the month of August

Hot-Humid Climate

From first principles, locating ducts inside conditioned space via unvented-cathedralized attic construction should have the most benefit in hot-humid climates due to the exclusion of exterior moisture 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 as to reduce the air temperature by 20° F.

Houston, Texas

New lessons were learned in the hot-humid climate application of unvented-cathedralized attics under asphalt composition shingles in production homebuilding. For a project in Houston, Texas, in order to keep the incremental cost as low as possible, the applications were made with netted and blown cellulose insulation under the roof sheathing rather than the previous expanding spray foam applications for custom houses. Monitoring of temperature and humidity conditions above and below the cathedralized insulation showed interesting and new results compared to hot-dry climate applications with tile roofs. Besides it being much more important to achieve a high level of air pressure boundary tightness to minimize air exchange with outdoors, it became apparent that solar driven moisture through composition shingles was an unknown but significant factor to be accounted for. During summertime and the adjoining swing seasons in hot-humid climates, nighttime roof temperatures are depressed below the ambient dew point temperature due to night sky radiation, causing moisture to condense on the surface of the roof. Thus, in the morning, the roofs are generally wet. It appears that some of this moisture is drawn into the material of the composition shingle, and between the laps of shingles. Solar radiation subsequently heats the roof surface, tremendously increasing the water vapor pressure and thermal gradients, which drives water vapor into and through the roof assembly. This happens whether the roof is vented or unvented, hence, vented attic dew point temperatures are also elevated above outdoors during sunshine hours.

Observations of elevated humidity conditions are coincident with the morning heating of the roof surface as shown in Figure 10. The solar powered vapor drive peaks about noontime, after which time the shingles are dry and the moisture 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 12. 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 or vapor permeable expanding foam. In addition, there appears 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 stops moving up and tends to concentrate as evidenced by some observations of elevated wood moisture content and rusted fasteners. However, the measured data in Figure 11 shows elevated dew point with increasing height only during daytime hours. This indicates that moisture removal by the space conditioning system is 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 retarder roof underlayment of 1 perm (water vapor transmission ASTM E96) or less beneath the composition shingles. Such roof underlayments are used instead of traditional 15 lb felt roofing paper, which has a water vapor transmission of about 6 perm, and are commercially available as Flexia Tri-Flex-30, Titanium UDL, and Typar RoofWrap 30 with water vapor transmission of about 0.54 perm. The material costs about $0.08/ft^2 or about 3 to 4 times that of 15 lb felt.

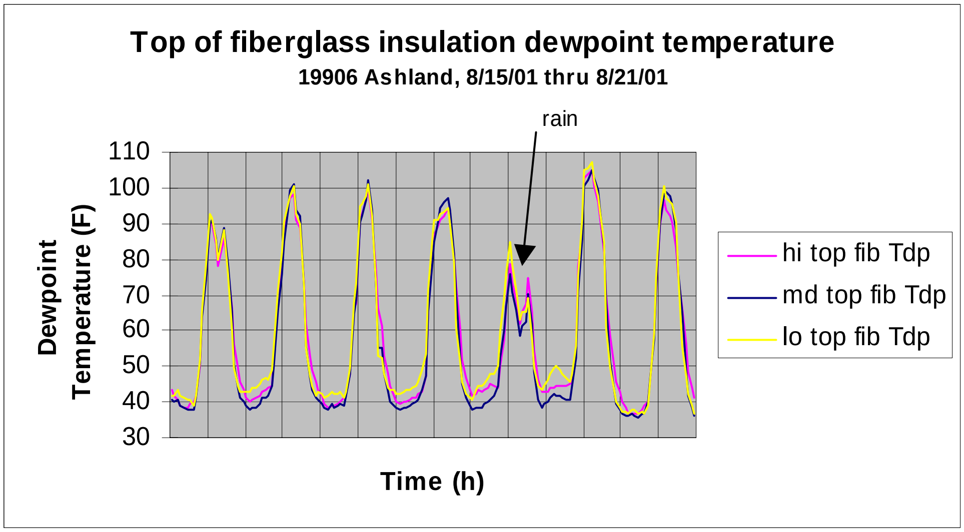

Figure 10 Observations of elevated humidity conditions are coincident with the morning heating of the roof surface, measured on top of the insulation at three heights in the cathedralized attic

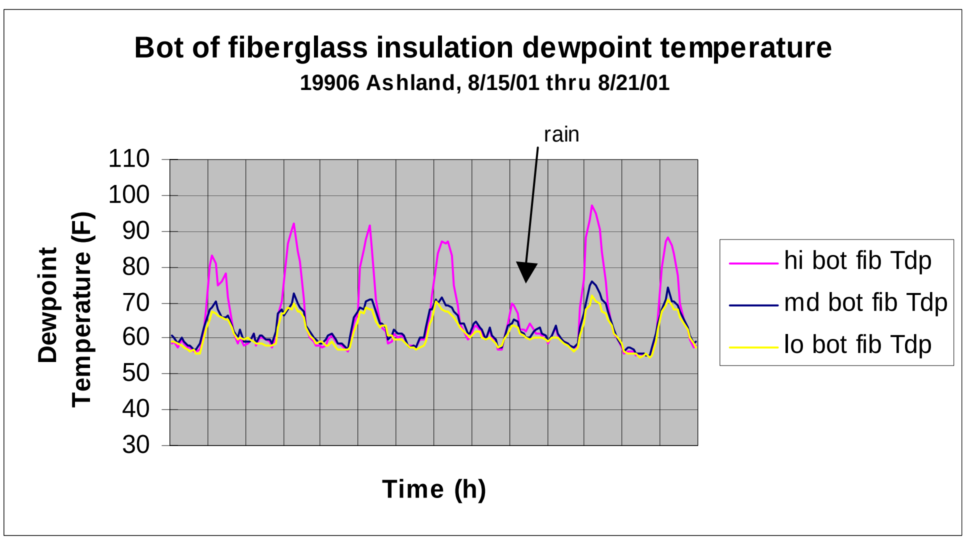

Figure 11 Observations of elevated dew point temperature with increasing height during daytime hours, measured at the bottom of the insulation at three heights in the cathedralized attic

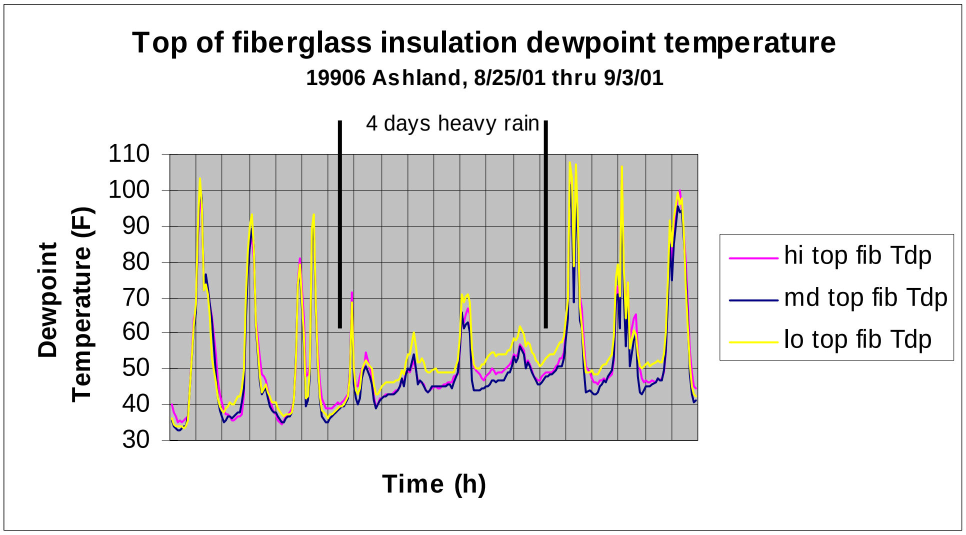

Figure 12 Even though the roof is wet, lack of sunshine during rain or overcast conditions mutes the water vapor drive into the roof assembly

For the particular house discussed here in Figures 10 through 16, two roof bays—one insulated with R-22 netted and densely packed cellulose and one with R-30 unfaced fiberglass batts, were instrumented with temperature and relative humidity 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 long, 8/12 pitch sloped roof faced south. Figure 17 shows the concurrent outdoor environmental conditions except for that of Figure 12.

Referring to Figure 13, hourly drybulb temperature measurements taken between the roof sheathing and the cathedralized insulation show the wide temperature swing between the early morning and late afternoon hours. Sheathing temperature peaked for a short time around 170° F, which is acceptable for the wood product.

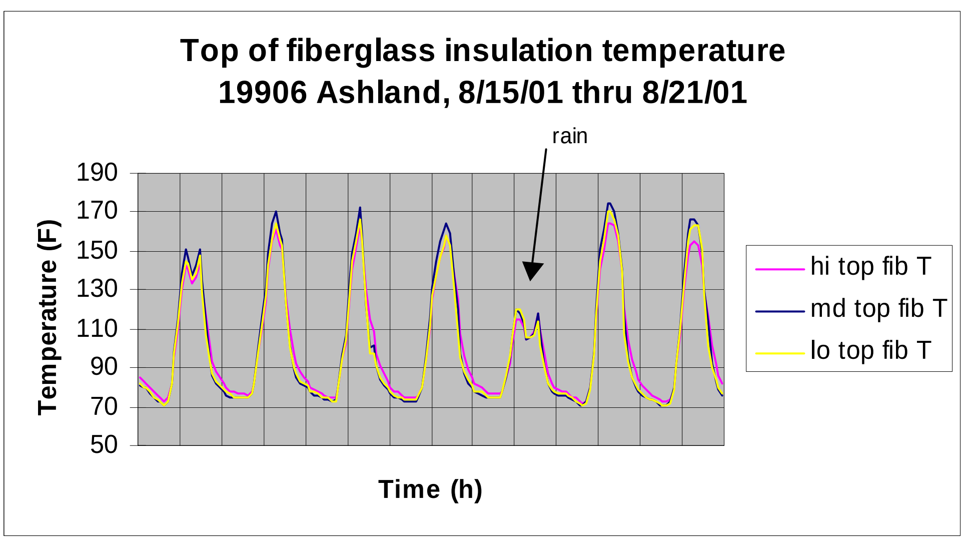

Figure 13 Hourly temperature measured between the bottom of the roof sheathing and the top of the R-30 fiberglass insulation

Referring to Figures 14 and 15, relative humidity at the interface between the top of the insulation and the roof sheathing stayed low, while relative humidity 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 16, dampened the near saturation moisture pulse seen with the fiberglass insulation.

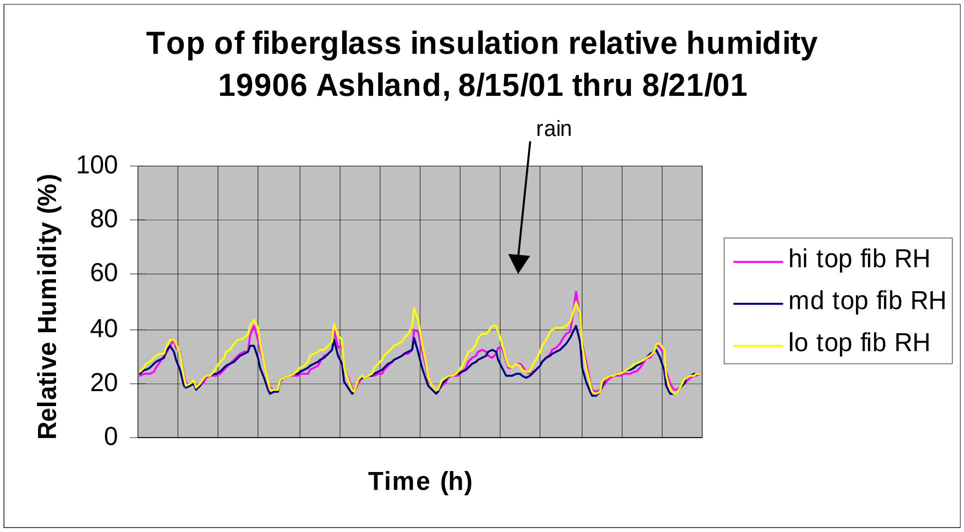

Figure 14 Hourly relative humidity between the roof sheathing and the insulation is always relatively low despite the solar driven moisture

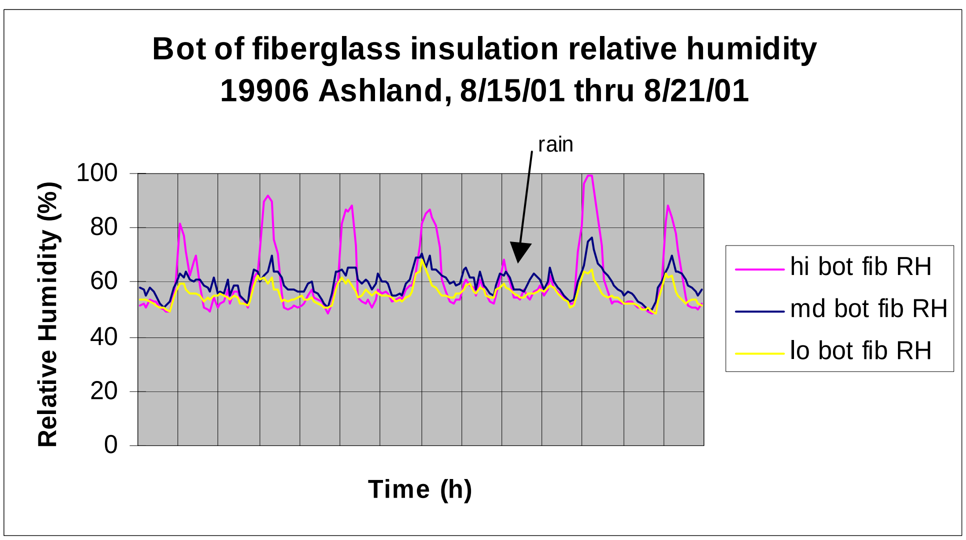

Figure 15 Hourly relative humidity at the bottom of the cathedralized R-30 fiberglass insulation, showing the elevated level, especially near the peak, as the roof moisture moves through

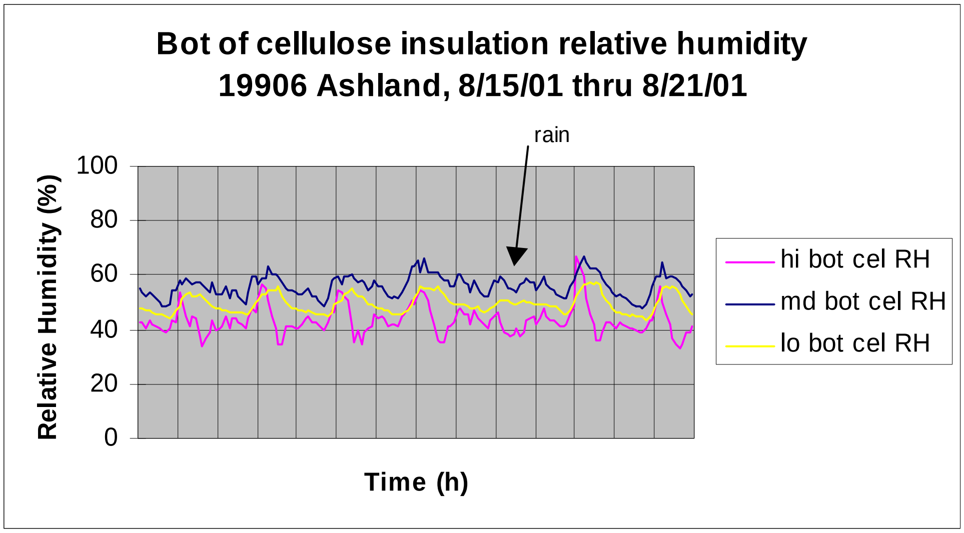

Figure 16 Hourly relative humidity at the bottom of the cathedralized R-22 cellulose insulation, showing how the moisture storage capacity of the cellulose dampens the moisture pulse through the assembly

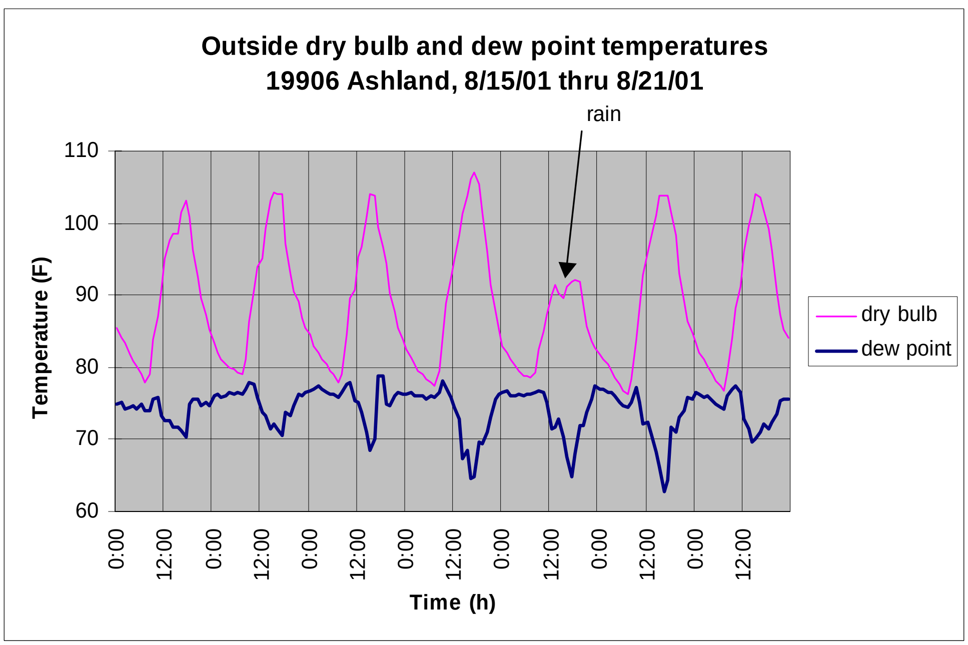

Figure 17 Hourly measurements of outdoor dry bulb and dew point temperature in Houston, TX

Jacksonville, Florida

A side-by-side study was conducted in Jacksonville, FL where an unvented-cathedralized attic house was directly compared to a similar vented attic house. Among other things, temperature was measured on all four cardinal orientations for the asphalt fiberglass composition shingles. Figures 18 and 19 show that, for the entire month of August 2001, the peak shingle temperature was 180° F and the peak shingle temperature difference was 7° F. On average over the whole month, the unvented-cathedralized 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 0.93° F for vented versus unvented attics in Miami. Parker and Sherwin (1998) previously reported a measured peak shingle temperature increase of 5° F due to a radiant barrier system.

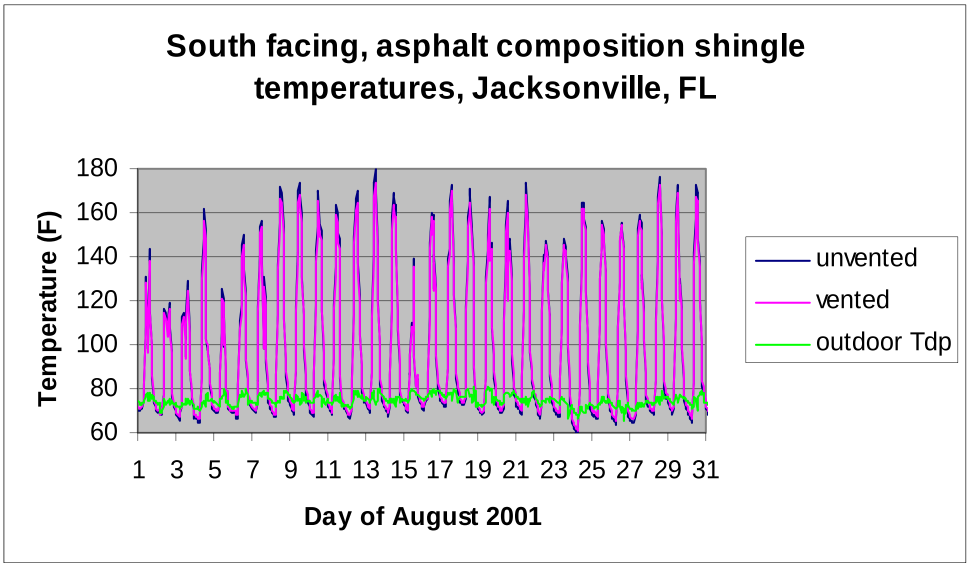

Figure 18 Hourly measurements of roof shingle temperature over vented and unvented-cathedralized attics in Jacksonville, Florida; also showing outdoor dew point temperature

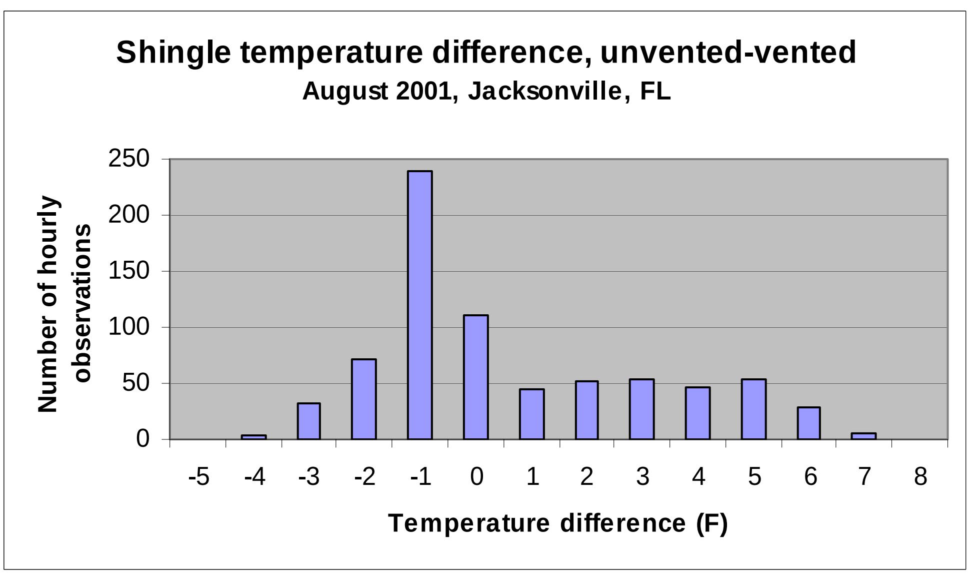

Figure 19 Histogram of roof shingle temperature difference over vented and unvented-cathedralized attics in Jacksonville, Florida

Figure 18 also illustrates the roof temperature depression, due to night sky radiation, which takes the roof temperature below the ambient air dew point temperature and causes condensation on the roof shingles.

Air temperature stratification in both the unvented-cathedralized 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, while the high attic was only 3° F warmer than the low attic on average.

In winter, if the roof sheathing temperature goes below the cathedralized attic air dew point temperature for long periods, condensation can occur on the bottom of the sheathing. This was observed near roof peaks in both Houston, TX and Jacksonville, FL with cellulose and fiberglass insulation, but not with low-density expanding foam. The low density expanding foam is permeable to water vapor (10 perm at 5 inch thickness), but unlike fiberglass and cellulose insulation, it is air impermeable (ASTM 2004). Because air does not move within or through the product, moisture is not carried to the cold roof sheathing, nor does it migrate up to peaks with air movement due to thermal buoyancy. Figure 20 shows wintertime roof sheathing temperature, for the worst-case north orientation, along with the cathedralized attic air dewpoint temperature. The north orientation receives the least solar heat, hence, the temperature remains cooler and the drying potential is lower.

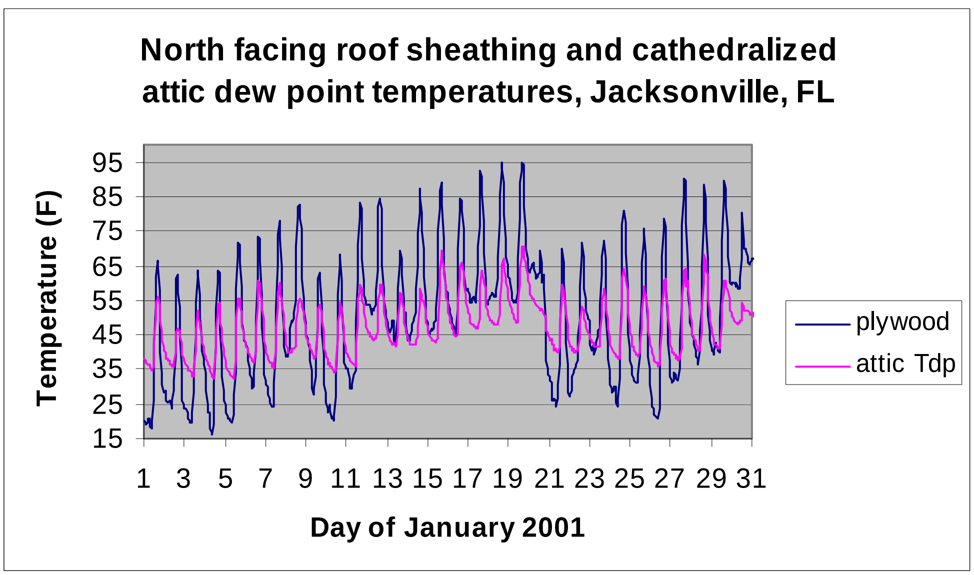

Figure 20 Hourly measurements of roof sheathing temperature and unvented-cathedralized attic dew point temperature in Jacksonville, Florida

<u>Lake City, Florida</u>

In February 2003, roof sheathing inspections were conducted at two houses in northern Florida to evaluate any potential moisture accumulation. That time of 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 with several cold weather events. Both houses had 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. 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 left at each house between the roof sheathing and the foam insulation. These monitors will record temperature and relative humidity every four hours for up to two years.

The roof sheathing showed no signs of moisture condensation, mold, discoloration, de-lamination, 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%.

Cold Climate

Application of the unvented-cathedralized 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 a significant energy inefficiency (Petrie 2004). Another common reason to cathedralize the attic insulation is to provide room for storage, or to leave unfinished space that may be finished later. This is more common in the colder northern climates than in the warmer southern climates.

However, due to cold sheathing temperatures for extended periods, it is important that certain design criteria be followed. The easiest way to avoid moisture condensation on sheathing with cathedralized attics in cold climates is to use air impermeable expanding spray foam applied continuously and directly to the underside of the roof sheathing and framing. 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. If higher relative humidity conditions will exist for extended periods (days to weeks), then a vapor retarder paint (1 perm or less) should be applied to the exposed air impermeable but water vapor permeable insulation. If vapor retarder paint is not used, then ventilation chutes should be fastened to the underside of the roof sheathing before the insulation is applied, and soffit to ridge ventilation should be employed.

If air permeable insulation will be used to cathedralize attics in climates with roof sheathing temperatures that dip below 45° F for days at a time, then rigid insulation must be installed above the structural roof sheathing to keep the roof sheathing temperature above 45° F (dew point at interior conditions of about 70° F dry bulb and 40% relative humidity). Tables 8 and 9 show how much rigid insulation would be required as a function of outdoor temperature, and total assembly R-value, with 70° F interior temperature.

<u>Minnesota, Wisconsin, Massachusetts</u>

Icynene® is an open cell polyicynene insulation with a published water vapor permeance of 16 perm at 3 inch thickness and 10 perm at 5 inch thickness. Some WUFI computer modeling has indicated that in cold climates in the range of 6000 heating degree days (HDD), moisture may accumulate to unsatisfactory levels in the structural roof sheathing above direct-applied Icynene insulation. 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 year was chosen to conduct the inspection since any potential moisture accumulation at the sheathing to insulation interface should be most evident at the end of a winter season.

At all of the sites investigated, at least one sample of direct-applied foam insulation was removed, intact, from within one to five feet of the roof peak. Removal of each sample exposed about a 10 inch square of roof sheathing. In some cases, other samples were taken from additional locations, including lower on the roof, and on walls not yet covered. The location near the roof peak was chosen to reflect the worst-case, since, over time, indoor air moisture conditions are most elevated at high points 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 observation and physical observations were made to indicate the presence of any bulk moisture, mold, wood discoloration, rot, wood deterioration or de-lamination. Then 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, which was calibrated for spruce-pine-fir (SPF) wood. While probing the roof sheathing with the moisture meter pins, any indication of wood softness was noted.

The removed insulation sections were replaced and re-sealed with polyurethane gun foam. A temperature and relative humidity sensor was left at four of the houses between the roof sheathing and the Icynene insulation, and another sensor was left to monitor air conditions near the peak of the roof. The monitors will record temperature and relative humidity every two hours for 11 months.

The tabulated results are shown in Table 7. There is a significant amount of solar induced drying that occurs on southern exposures where the sheathing moisture content was generally much lower than on northern exposures. There is less of a difference between east and west orientations, but, generally, west exposures were drier than east, and both were drier than north.

Where water events causing high indoor humidity exist, especially with little or no mechanical ventilation to provide air exchange with outdoors, conditions can exist in very cold climates whereby enough water vapor diffuses through the Icynene insulation to raise the roof sheathing moisture content above satisfactory levels, and cause observable bulk water condensation in some cases.

For example, the house at MN1 had experienced a flooded basement floor about a week before our visit (about 1 inch of water). The basement was simply left to dry up through the house, causing the high humidity conditions in the unvented-cathedralized 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, infrequently occupied, and in an unfinished state with exposed Icynene on the roof and most of the walls. However, it remains unknown what caused the high humidity conditions. It may have been the drying of the 2-inch concrete slab poured for radiant heat, but we don't yet know when that slab was poured. The house also had no ventilation system operating.

Considering the severe cold climate (> 9000 HDD), 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 four houses in Minnesota and Wisconsin. Yet, having said that, there were no observations of fungi or wood deterioration, which indicates that the system is forgiving and probably dries out quickly enough with warmer weather and solar heat.

In general, except for the coldest climates and exceptionally high indoor relative humidity, the roof sheathing above direct-applied Icynene was found to be in good condition. Based on these limited data, at least one of the following measures should be taken when Icynene is used under roof sheathing in climates with more than 9000 heating degree-days (65^{o}F base):

1. Wintertime indoor moisture conditions should not rise above 35% relative humidity for extended periods (days). Increased outdoor air exchange or dehumidification may be required, but certainly, controls on any humidification equipment should be limited to 35% relative humidity.
2. Application of vapor barrier paint (< 1 perm) to the Icynene foam, assuring good coverage over the uneven surface.
3. Along with soffit and ridge ventilation, extruded polystyrene roof ventilation chutes should be fastened to the underside of the roof sheathing, in an overlapping fashion from the peak down to the soffit, before the Icynene is sprayed. This will have multiple beneficial effects, including:
    a) venting any moisture that gets above the insulation;
    b) reducing the water vapor permeance of the entire insulation assembly;
    c) further avoidance of any ice dam formation at eaves;
    d) increased ability of the roof sheathing to dry in the event of incidental water leakage
    c) drainage of any melted snow that may drift into ridge or soffit vents.

More data should be taken in cold climates, and these data should be used to help verify the ability of the WUFI computer model to predict measured conditions.

Table 7 Moisture measurement and observation results

Location	HDD (65)	House ID	Mo/Yr Insulated	Sample ID	Insulation Type	Insulation Thickness (inch)	Roof Sheathing Type	Roofing Type	Roof Orientation (N,E,S,W)	House RH (%)	Attic RH (%)	Attic T (F)	Sheathing Moist. Content Range (%)	Framing Moist. Content Range (%)	Appearance of sheathing	Hobo T/RH loggers left
Minnesota:																
Duluth	9906	MN1	Nov-01	MN1a	Icynene	4-6	plywood	comp shingle	S, mid	44	70	68	12-17	11-12	good condition	N+S+air
				MN1b	Icynene	3-5	plywood	comp shingle	N, mid	44	70	68	>40	11-12	wet, no mold-stain-rot, nail rust	
				MN1c	Icynene	5-8	plywood	comp shingle	N, east	44	70	68	>40	11-12	damp, no mold-stain-rot, nail rust	
				MN1d	Icynene	5-7	plywood	comp shingle	S, east	44	70	68	12-16	11-12	good condition	
Duluth	9906	MN2	Nov-01	MN2a	Icynene	4-7	old boards	comp shingle	N, west		40-50	70-78	26-31	9-10	good condition	N+air
				MN2b	Icynene	4-7	old boards	comp shingle	S, west		40-50	70-78	7-10	9-10	good condition	
				MN2c	Icynene	4-7	old boards	comp shingle	N, east		40-50	70-78	25-28	9-10	good condition	
				MN2d	Icynene	4-7	old boards	comp shingle	S, east		40-50	70-78	8-9	9-10	good condition	
				MN2e	Icynene	4-7	old boards	comp shingle	N, mid		40-50	70-78	27-30	9-10	good condition	
Kelsey	9906	MN3	??-02	MN3a	Icynene	4-7	OSB	comp shingle	N, west		30	72	20-25	7-8	good condition	none
				MN3b	Icynene	3-7	OSB	comp shingle	S, east		30	72	16-19	7-8	good condition	
Duluth area	9906	MN5	??-02	MN5a	Comfort	3	OSB	comp shingle	N		30	73	6-7	<6	good condition	none
Wisconsin:																
Danbury	9061	MN4	??-01	MN4a	Icynene	6-9	OSB	comp shingle	W, north	53	>85	71	>40	6-8	not wet, no mold-stain-rot,	W,north+air
															nail rust, OSB softer than normal	
				MN4b	Icynene	6-9	OSB	comp shingle	E, north	53	>85	71	>40	6-8	same as west	
				MN4c	Icynene	6-9	OSB	comp shingle	S (gable wall)	53	75	71	21-23		easier to push probe than normal	
				MN4d	Icynene	6-9	OSB	comp shingle	E, mid, low	53	64	71	25-38			
				MN4e	Icynene	5.5	OSB	wood siding	E (high wall)	53		71	24-33			
				MN4f	Icynene	5.5	OSB	wood siding	W (mid wall)	53		71	25-30			
Massachusetts:																
Somerville	5596	MA1	??-03	MA1a	Icynene	6-8	old boards	slate	E, north	30	30	68	16-18	10-12	good condition	E,north+air
				MA1b	Icynene	6-8	old boards	slate	W, north	30	30	68	12-15	10-12	good condition	
				MA1c	Icynene	6-8	old boards	slate	E, south	30	30	68	13-17	10-12	good condition	
				MA1d	Icynene	6-8	old boards	slate	W, south	30	30	68	11-13	10-12	good condition	

BUILDING CODE CONSIDERATIONS

International Residential Code Activities

Direct input to the USDOE code change proposal to the International Residential Code (IRC), and involvement at the code hearings, resulted in approval of conditioned attic assemblies. The approved wording in the IRC is as follows:

R806.4 Conditioned attic assemblies: Unvented conditioned attic assemblies (spaces between the ceiling joists of the top story and the roof rafters) are permitted under the following conditions:

1. No interior vapor retarders are installed on the ceiling side (attic floor) of the unvented attic assembly.
2. An air-impermeable insulation is applied in direct contact to the underside/interior of the structural roof deck. "Air-impermeable" shall be defined by ASTM E 283.

   Exception: In zones 2B and 3B, insulation is not required to be air impermeable.

3. In the warm humid locations as defined in N1101.2.1:
   a. For asphalt roofing shingles: A 1 perm or less vapor retarder (determined using Procedure B of ASTM E 96) is placed to the exterior of the structural roof deck; i.e. just above the roof structural sheathing.
   b. For wood shingles and shakes: a minimum continuous 1/4-inch vented air space separates the shingles/shakes and the roofing felt placed over the structural sheathing.
4. In zones 3 through 8 as defined in N1101.2 sufficient insulation is installed to maintain the monthly average temperature of the condensing surface above 45° F. The condensing surface is defined as either the structural roof deck or the interior surface of an air impermeable insulation applied in direct contact to the underside/interior of the structural roof deck. "Air-impermeable" is quantitatively defined by ASTM E 283. For calculation purposes, an interior temperature of 68° F is assumed. The exterior temperature is assumed to be the monthly average outside temperature.

Since that work was begun, efforts have continued to improve the ease of application of the unvented conditioned attic assembly by creating draft prescriptive tables that may be proposed for inclusion in the code. Tables 8 and 9 were developed based on field experience as described earlier in this document and based on first-condensing-plane temperature calculations. The first-condensing-plane temperature calculations were based on a requirement to keep the structural roof sheathing, located above air permeable insulation, above the wintertime interior dew point temperature. The wintertime interior dew point temperature was fixed at 45° F, which corresponds to 70° F and 40% relative humidity. The dry bulb temperature difference across the roof assembly was calculated as the difference between an indoor condition of 70° F and an outdoor condition of 8° F above the ASHRAE 99% Heating Design temperature (ASHRAE, 2001), except for the hot-dry climate zone 2B, which was 15° F above the ASHRAE 99% heating design temperature.

Table 8 Draft prescriptive requirements for conditioned attic assemblies by climate zone with a total assembly thermal resistance of 30 Btu/h-ft^2-F

Description	IECC Zone	All roofing types (asphalt, clay, cement, metal, wood, plastic) Asphalt must have < 0.55 perm underlayment; Wood must have 1/4" minimum vented air space below	
		Air-impermeable insulation	**Air-permeable insulation (R-30 total assembly)**
Hot-humid	1A	no restriction	no restriction
Hot-humid	2A	no restriction	R-8 above the structural roof sheathing
Hot-dry	2B	no restriction	no restriction
Warm-humid	3A (below humid line)	no restriction	R-11 above the structural roof sheathing
Warm-humid	3A (above humid line)	no restriction	R-14 above the structural roof sheathing
Warm-dry	3B (not Texas)	no restriction	Tile roofs only
Warm-dry	3B (Texas)	no restriction	R-5 above the structural roof sheathing
Warm-marine	3C	no restriction	R-2 above the structural roof sheathing
Mixed-humid	4A	no restriction	R-17 above the structural roof sheathing
Mixed-dry	4B	no restriction	R-13 above the structural roof sheathing
Mixed-marine	4C	no restriction	R-11 above the structural roof sheathing
Cold	5A, 5B	no restriction	R-18 above the structural roof sheathing
Very Cold	6A, 6B, 7A, 7B	vapor retarder paint on bottom surface (1 perm max)	R-21 above the structural roof sheathing

Table 9 Draft prescriptive requirements for conditioned attic assemblies by climate zone with a total assembly thermal resistance of 38 Btu/h-ft^2-F

Description	IECC Zone	All roofing types (asphalt, clay, cement, metal, wood, plastic) Asphalt must have < 0.55 perm underlayment; Wood must have 1/4" minimum vented air space below	
		Air-impermeable insulation	**Air-permeable insulation (R-30 total assembly)**
Hot-humid	1A	no restriction	no restriction
Hot-humid	2A	no restriction	R-10 above the structural roof sheathing
Hot-dry	2B	no restriction	no restriction
Warm-humid	3A (below humid line)	no restriction	R-13 above the structural roof sheathing
Warm-humid	3A (above humid line)	no restriction	R-18 above the structural roof sheathing
Warm-dry	3B (not Texas)	no restriction	Tile roofs only
Warm-dry	3B (Texas)	no restriction	R-6 above the structural roof sheathing
Warm-marine	3C	no restriction	R-3 above the structural roof sheathing
Mixed-humid	4A	no restriction	R-22 above the structural roof sheathing
Mixed-dry	4B	no restriction	R-16 above the structural roof sheathing
Mixed-marine	4C	no restriction	R-14 above the structural roof sheathing
Cold	5A, 5B	no restriction	R-23 above the structural roof sheathing
Very Cold	6A, 6B, 7A, 7B	vapor retarder paint on bottom surface (1 perm max)	R-27 above the structural roof sheathing

Florida Activities

Code jurisdictions in the majority of counties in Florida have approved the unvented-cathedralized attic approach with air impermeable expanding foam applied directly to the underside of the roof sheathing. The efficiency and moisture control benefits are clear. However, in some cases, a jurisdiction may disallow it right next to another jurisdiction that allows it. The usual reason for rejection is that "the code requires attics to be vented." Building officials have the duty to review and the right to approve construction methods that meet or exceed the intent of the code. However, it can be a time consuming, expensive, and sometimes frustrating task to seek approval jurisdiction by jurisdiction. Therefore, significant effort has been made to gain approval through the State building code. A code change modification was submitted that addressed all parts of the building code that referred to required attic ventilation, however, it failed to achieve majority approval by the Commission in year 2003. The next code change cycle will not be until 2006, but new efforts are underway, in part supported by the Florida Department of Community Affairs and the Florida Engineering Society, to bring this matter to the fore again. Information exchange and discussion has begun at high levels and is being supported by USDOE Building America research, publications, and presentations.

California Title 24 Activities

Over the last three years, unvented-cathedralized conditioned attic assemblies, under tile roofs, have been constructed in California under the Title 24 energy code. Approval was given to take the efficiency credit for ducts inside conditioned space as long as active conditioning was installed in the unvented-cathedralized attic, complying with the code definition of conditioned space. While this meets the code, active conditioning of the unvented-cathedralized space creates and extra expense in material and labor for the builder and extra expense in energy consumption for the occupants. As shown in Tables 5 and 6, and Figures 1 and 2 above, the cooling and heating season temperature differences between the attic and living space are small even with the space conditioning air flow shut off, as was the case in these houses. Simulations by Walker (2004) have shown the same temperature results, and suggest that there is a slight energy penalty associated with actively conditioning that space due to a roughly 2° F temperature difference increase across the insulated roof assembly.

Work is ongoing to gain approval within Title 24 for the unvented-cathedralized conditioned attic assembly without active conditioning of that space. We will propose that the house be tested by fan depressurization, with the attic access open, to a tightness criteria of 0.25 ft^3/min per ft^2 of building surface area, tested at 50 Pa pressure differential with respect to outdoors.

CONCLUSIONS

A number of monitoring and testing studies have been conducted to quantify the performance of the unvented-cathedralized conditioned attic approach for which the main purpose is to enclose thermal air distribution systems within conditioned space to increase efficiency, comfort, indoor air quality durability, and maintainability. Data has shown that these attic spaces operate very near the conditions of the living space without active conditioning. Active conditioning is unnecessary, but can be useful in humid climates for a few months for new construction drying. It has been shown that increased vapor diffusion resistance is needed beneath asphalt roofing materials. 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, similar to the peak effect of radiant barriers. If air permeable insulation is used, rigid insulation must be placed above the structural roof sheathing except in IECC zones 1, 2B, and 3B except Texas. Building code bodies are responding favorably, but more work needs to be done.

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