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Sealed attic construction, by excluding vents to the exterior, can be a good way to exclude moisture-laden outside air from attic and may offer a more easily constructed alternative for air leakage control at the top of residential buildings. However, the space conditioning energy use and roof temperature implications of this approach have not been extensively studied. A computer modeling study (Rudd 1996) was performed to determine the effects of sealed residential attics in hot climates on space conditioning energy use and roof temperatures. The one-dimensional, finite element computer model (FSEC 1992) contained an attic model developed and validated by Parker et al. (1991). Empirical modifications were made to the attic model to provide better alignment with measured ceiling heat flux reductions of ventilated attics with respect to sealed attics for summer peak days from three roof research facilities (Beal et al. 1995; Rose 1996; Fairey 1986). Annual and peak cooling day simulations were made for the Orlando, Florida, and Las Vegas, Nevada, climates, using a 139 m_2 (1500 ft_2) slab-on-grade ranch style house with wood frame construction. Results showed that, when compared to typically vented attics with the air distribution ducts present, sealed "cathedralized" attics (i.e., sealed attic with the air barrier and thermal barrier [insulation] at the sloped roof plane) can be constructed without an associated energy penalty in hot climates.

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Vented and Sealed Attics In Hot Climates

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ABSTRACT

Sealed attic construction, by excluding vents to the exterior, can be a good way to exclude moisture-laden outside air from attics and may offer a more easily constructed alternative for air leakage control at the top of residential buildings. However, the space conditioning energy use and roof temperature implications of this approach have not been extensively studied. A computer modeling study (Rudd 1996) was performed to determine the effects of sealed residential attics in hot climates on space conditioning energy use and roof temperatures. The one-dimensional, finite element computer model (FSEC 1992) contained an attic model developed and validated by Parker et al. (1991). Empirical modifications were made to the attic model to provide better alignment with measured ceiling heat flux reductions of ventilated attics with respect to sealed attics for summer peak days from three roof research facilities (Beal et al. 1995; Rose 1996; Fairey 1986). Annual and peak cooing day simulations were made for the Orlando, Florida, and Las Vegas, Nevada, climates, using a 139 m^2 *(1500 ft*^{2}*) slab-on-grade ranch style house with wood frame construction. Results showed that, when compared to typically vented attics with the air distribution ducts present, sealed "cathedralized" attics (i.e., sealed attic with the air barrier and thermal barrier [insulation] at the sloped roof plane) can be constructed without an associated energy penalty in hot climates.*

INTRODUCTION

The rationale behind this attic ventilation study was primarily twofold:

1. The need to solve problems related to the entry of moisture-laden outside air in hot-humid climates (ASHRAE 1997), such as condensation on cooling ducts and interior mold.
2. The need to obtain a tight air infiltration barrier at the top of residential buildings in hot climates to reduce energy consumption.

Ventilation is one of the most effective ways to deal with humidity problems in heating climates, but ventilation can be one of the major causes of humidity problems in southern humid climates (Lstiburek 1993). The problem of condensation in attics in hot-humid climates is caused by humid outdoor air coming in contact with cold surfaces in the attic. Although worse in coastal areas, this problem is not confined to them. The most offending cold surfaces are usually supply ducts, but they can be ceiling drywall and metallic penetrations through the ceiling if low interior setpoints are maintained. In much of Florida, it is not uncommon to have an outdoor air dew point of 24°C (75°F) and an attic air dew point of 29°C (85°F). When an attic surface temperature is lower than the attic air dew point, condensation will occur.

The attic air dew point can be higher than the outdoor air dew point because moisture stored in the wood roof framing at night is released during the day. This moisture adsorption-desorption process is driven by the relative humidity gradient between surfaces and the air in contact with those surfaces. Relative humidity of air at a surface is that of air in equilibrium with the surface moisture content of the material. The result of this attic moisture adsorption-desorption mechanism is summarized as follows:

Nighttime:

High attic air relative humidity due to air exchange with outdoors

- Lower air relative humidity at the surface of wood framing materials resulting in moisture being adsorbed by the wood framing materials
- Attic air dew-point temperature similar to outdoors

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Daytime:

- Lower attic air relative humidity due to sensible heat gain by solar
- Higher air relative humidity at the surface of wood framing materials resulting in moisture being desorbed by the attic framing materials
- Attic air dew-point temperature elevated above outdoors

The greatest problem with attic condensation will occur during the daytime when the air-conditioning (cooling) system operates for long periods, causing supply ducts, supply diffusers, and ceiling areas near supply diffusers to remain cold. With normal supply temperatures between 10°C and 13°C (50°F and 55°F), and attic air dew-point temperatures up to 29°C (85°F), it is easy to see how condensation can occur. Obviously, duct insulation, with the proper thermal resistance and surface emittance and properly installed to avoid insulation compression, can minimize condensation potential on ducts. However, the ducts must not only be insulated but also sealed against air leakage. Cold air leaking from supply ducts, creating cold surfaces in the moist attic environment, can also cause condensation-related problems.

Moving the entire air distribution system out of the attic and into conditioned space is good but is often impractical or impossible due to design and cost constraints. In the hot-humid climate, the best solution to eliminate the potential for moisture condensation in attics may be to keep the moisture out of the attic altogether by sealing the attic to the outdoors. TenWolde and Burch (1993) recommended that the roof cavities of manufactured homes not be ventilated in hot-humid climates due to conditions that could be conducive to mold and mildew growth (monthly mean surface relative humidity above 80%). A later report by Burch et al. (1996) came to the same conclusion, stating that their computer modeling results for Miami, Florida, “indicate that ceiling vapor retarders and roof cavity vents should not be installed in homes exposed to hot and humid climates.” In many cases, roofing layers that provide rain-proofing can also provide air sealing, and if stucco is used for the exterior wall finish, it can be easy to seal the fascia, soffit, and rake areas with stucco also. This would provide an attic that was sealed from outdoor air exchange, effectively excluding the moisture-laden air.

Another attic condensation problem, separate from the one discussed above but still related to outside moisture entering the attic through attic vents, sometimes occurs with metal roofing and an attic radiant barrier. In this case, condensation forms at night on the underside of metal roofing or radiant barrier exposed to humid attic air. Due to night sky radiation, the metal roof or radiant barrier temperature can be depressed below the attic air dew-point temperature, allowing condensation and possible water damage to ceiling materials to occur. In predominantly hot-humid climates, attics sealed to outside air exchange would correct this problem.

In modern residences, the challenge of achieving a continuous air infiltration barrier and thermal insulation barrier at the interior ceiling level is especially difficult. The air barrier, used to isolate the living space from the attic, is usually the taped drywall, while the thermal barrier is the insulation placed on top of the drywall. Typically, the ceiling is not a single horizontal plane but a series of horizontal planes, vertical planes (knee walls), and sloped planes, all intersecting to create the ceiling. Field inspections repeatedly show how the continuity of the air barrier and thermal barrier is compromised at knee walls, coffered ceilings, dropped ceilings, framed soffits or mechanical chases, recessed canister lights, fireplace flues or chimneys, and penetrations for plumbing, electrical, and space conditioning, etc. In reality, it is often impractical to try to maintain air and thermal barrier continuity at all of these locations. Airtight recessed cannister lights rated for insulation contact, foam sealing of penetrations, and full-depth blown insulation to cover the variations in ceiling plane can help to alleviate the problems, but at significant added cost.

The most cost-effective location to both air seal and insulate the attic may be at the roof plane rather than the interior ceiling plane. Where attic insulation is placed along the underside of the roof sheathing, this has been referred to as “cathedralized” residential attic construction (Rose 1995). In “cathedralized” construction, there may still be roof plane changes that create knee wall areas, such as build-over roofs where girder trusses are used, but these are usually few and relatively easy to access. In many cases, the roof layer (sheathing, roofing paper, flashing) that provides rain-proofing can also provide air leakage control. Some additional air sealing may be necessary at roof penetrations for vents and exhaust ducts. If stucco is used for the exterior wall finish, the fascia, soffit, and rake areas can be finished with stucco as well to provide an attic that is restricted from outdoor air exchange.

Another outcome of using the roof plane to create the air and thermal barrier is that the enclosed attic space is essentially inside the conditioned space. This space can be used to locate the space conditioning equipment and the air distribution system, and possibilities for additional storage are available. Also, the mechanical systems (electrical, plumbing, HVAC) placed in the attic are left exposed and accessible in the event of the need for repair or remodeling.

Current building codes across the United States require attic ventilation. In cold climates, the primary purpose of attic ventilation is to maintain a cold roof temperature to avoid ice dams created by melting snow (Tobiasson et al. 1994) and to vent moisture that moves from the conditioned space to the attic (Rose 1992; Lstiburek 1988; Spies 1987; Gatsos 1985). Melted snow, in this case, is caused by heat loss from the conditioned space. When water from melted snow runs out over the unheated eave portion of the house, it freezes and expands, often driving its way back up the roof and between shingles. In cathedral ceiling areas, a minimum one-inch air space is required between the roof sheathing and insulation, extending from soffit to ridge. In predominantly cold climates, for cathedral and “cathedralized” ceilings, a vented air chute

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that ensures an air gap between the roof sheathing and the insulation is the critical factor in controlling moisture accumulation in the sheathing (Rose 1995).

In hot climates, the primary purpose of attic ventilation is to expel solar-heated hot air from the attic to lessen the building cooling load. TenWolde and Carll (1992) also observed that "during summer, attic vents provide some cooling, but with sufficient ceiling insulation, the effect on cooling loads should be minor." Roof shingle temperatures will be higher during no-wind conditions, leading to a higher heat load on the attic. Therefore, the greatest need for attic ventilation is when there is little wind pressure to force air in and out of the attic; then, stack effect is the prime air mover, driven by the attic to outside air temperature difference. Relying on stack effect alone can require such large vents that it is difficult to prevent rain entry (Ledger 1990).

The required amount of ventilation area is measured by a unit termed "net free vent area." The net free vent area is the actual, unobstructed area where air can freely flow from outside to inside to outside. Most estimable manufacturers provide documentation of the net free vent area with their product, although a standardized test has not been universally adopted (Sullivan 1994). The building codes usually report the required ventilation area as a ratio of the net free vent area to the horizontal projection of attic floor area (i.e., 1:300 or 1:150). Typically, if at least 50% of the ventilating area is in the upper portion of the space and a continuous ceiling vapor retarder in cold climates is installed on the warm side, the required ratio is 1:300; otherwise, it is 1:150 (Hutchings 1998).

Sealed attic construction, by excluding vents to the exterior, can be a good way to exclude moisture-laden outside air from attics and may offer a more easily constructed alternative for air leakage control at the top of residential buildings. However, the space conditioning energy use and roof temperature implications of this approach have not been extensively studied.

COMPUTER MODEL SETUP

To evaluate the effects of sealed attics in hot climates on space conditioning energy use and roof temperatures, a computer modeling study was conducted for the Orlando, Florida, and Las Vegas, Nevada, climates. The computer model utilized was the FSEC 3.0 program (FSEC 1992) containing the attic model developed and validated by Parker et al (1991). The one-dimensional, finite-element program calculates combined heat and mass transfer, including conductive, convective, and radiant heat transfer, and lumped moisture modeling by the Effective Penetration Depth Method (Kerestecioglu 1989). Hourly simulations are performed using Typical Meteorological Year (TMY) weather data. In addition to building loads and heating and cooling system loads, individual surface temperatures and heat fluxes can be obtained, as well as air temperature and humidity ratio. Similar to a temperature setpoint, an optional humidity setpoint can be specified. The cooling system load will reflect the appropriate change in latent load, and if the specified equipment cannot meet the load, that will be reflected in the indoor air conditions. A real cooling machine performance model is used to calculate the air conditions leaving the cooling coil. A real thermostat model is also employed (Henderson 1992).

The reference house configuration used was a one-story, 139 m^2 (1500 ft^2) house that had been used in the past for many building energy modeling studies. Figure 1 shows a plan view of the house. The main house roof geometry is a 22.6 degree (5/12 pitch) hip roof with the ridge running east to west. Another hip roof runs over the garage, with that ridge running north to south. Table 1 lists the characteristics that were common to the Orlando and Las Vegas reference houses. The characteristics specific to the Orlando reference house are listed in Table 2. Model inputs were parametrically varied to isolate the effect of the item(s) in question. Table 3 lists the values that were changed for each Orlando simulation, along with a comment regarding the research question being asked. The characteristics specific to the Las Vegas reference house are listed in Table 4. Table 5 lists the parametrically varied model inputs for each Las Vegas simulation, along with a comment regarding the question being asked.

An early attic model (Fairey and Swami 1992), used primarily for modeling the performance of attic radiant barrier systems, treated the attic as two zones, an upper zone and a lower zone. An improved two-zone attic model (Parker et al. 1991), used in the FSEC 3.0 program, accounts for detailed radiation, buoyancy, and wind-driven airflows and thermal stratification within the attic airspace. The upper attic zone airflow was driven by wind, and the soffit inlet area was treated as an orifice with a discharge coefficient. The upper attic zone had a defined thickness and ran parallel to the bottom of the roof sheathing. The lower attic zone encom-

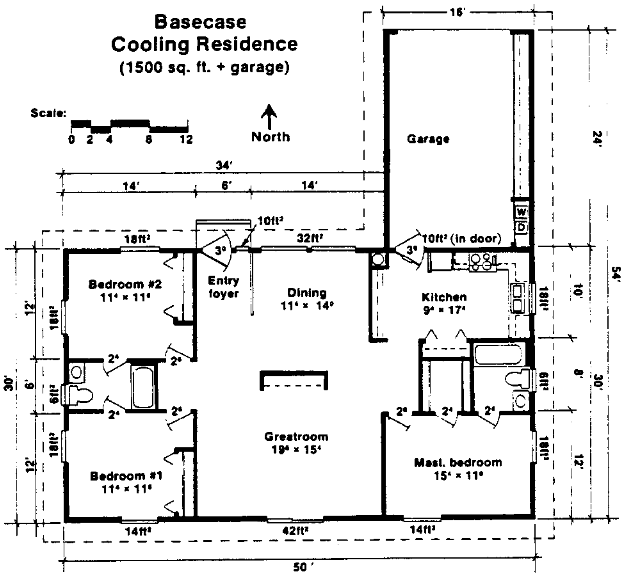

Figure 1 *Plan view of the reference house.*

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TABLE 1
Characteristics Common to Both the Orlando and Las Vegas Reference Houses

Component	
Construction type	Wood frame
Foundation type	Slab-on-grade
Roof type	Hip
Floor area	1500 ft^2 (139.4 m^2)
Window area	224 ft^2 (20.8 m^2)
Door area	20 ft^2 to outdoors 20 ft^2 to garage
Roof overhang	2 ft (0.61 m)
Roof solar absorptance, onyx black asphalt shingles, (Parker 1993)	0.966
Roof solar absorptance, white tile, (Parker 1993)	0.35
Roof infrared emittance	0.9
Attic plywood infrared emittance	0.8
Wall solar absorptance	0.75
Wall infrared emittance	0.9
Heating system	Electric resistance
Cooling system	DX vapor compression, SEER=10.0
Duct insulation R-value	5 hr-ft^2-F/Btu (0.88 m^2·K/W)
Duct location	In attic, unconditioned space
Duct leakage	None
Heating setpoint	72°F (22.2°C)
Cooling setpoint	77°F (25°C)
Humidity setpoint	Not specified, indoor humidity determined by the cooling machine performance
Internal gains	84.3 kBtu/day (24.7 kWh/day)
Air Infiltration, Effective Leakage Area	Calculated each hour, ELA = 99.2 in^2 (0.064 m^2)

TABLE 2
Orlando Specific Reference House Characteristics

1:300 attic ventilation
R-19 insulation on flat ceiling
R-11 wall insulation
Single glazing, aluminum frame

passed the remaining volume of the attic, and airflow was driven by buoyancy forces due to the hot air convecting upwards. Inlet air for the lower attic also entered through the soffit. The total airflow, from both the upper attic and lower attic, exited at the ridge. Convection coefficients were calculated as a function of temperature difference for the lower attic insulation surface and as a function of temperature difference and velocity for the upper attic roof plywood bottom surface.

The attic model (Parker et al. 1991) contained in the FSEC 3.0 program was empirically modified in order to align it with measured data from three roof research facilities (Beal and Chandra 1995; Rose 1996; Fairey 1986). Model alignment

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TABLE 3
Orlando Parametric Simulations

Simulation Number	Input Deck Changes From Reference Case	Research Question Asked
1	1:150 Attic Ventilation	Effect of increasing attic ventilation area from current Orlando building code
2	Sealed Attic, R-19 insulation on flat ceiling	Effect of just sealing attic
3	Sealed Attic, R-28 insulation on flat ceiling	Effect of sealing attic and increasing insulation
4	Sealed Attic, R-19 insulation under roof slope	Effect of sealing attic and moving insulation under roof slope (air and thermal barrier at roof plane)
5	Sealed Attic, R-28 insulation under roof slope	Effect of sealing attic and moving insulation under roof slope and increasing insulation
6	White Tile Roof	Effect of white tile roof alone
7	Sealed Attic, R-19 insulation under roof slope, White Tile Roof	Effect of sealing attic and moving insulation under roof slope and using white tile on roof
8	Sealed Attic, R-28 insulation under roof slope, White Tile Roof	Effect of sealing attic and moving insulation under roof slope and increasing insulation and using white tile on roof
9	Ducts In Conditioned Space	Effect of placing ducts inside conditioned space (conduction heat transfer effect only, no duct leakage)
10	Duct Leakage, 10% Return Side, 5% Supply Side, (Return leak comes from: 70% attic, 20% garage, 10% outdoors)	Effect of average amount of duct leakage (Based on measurements from 160 Florida homes, the average return side leak was 11% of the total flow, and the estimated average supply side leak was 5% (Cummings 1991))
11	Duct Leakage, 15% Return Side, 10% Supply Side	Effect of greater than average amount of duct leakage

TABLE 4
Las Vegas Specific Reference House Characteristics

1:150 attic ventilation
R-28 insulation on flat ceiling
R-19 wall insulation
Double glazing, vinyl frame

was performed using comparable vented vs. sealed measured data with insulation on the flat ceiling. The flat ceiling insulation configurations, both vented and sealed, involve solutions of combined conductive, convective, and radiant heat transfer in an environment where complex convection and radiation are dominant. In contrast, the sealed cathedralized attic is a relatively straightforward conduction-dominated heat transfer problem.

The means for empirical alignment of the attic model with the measured data was a combination of adjusting two parameters as a function of vent area:

1. The convection coefficient at the top of the flat ceiling insulation, as calculated by the Parker model, was reduced by a factor of 0.25 for the 1:300 case and by 0.5 for the 1:150 and 1:120 cases. The convection coefficient was increased by a factor of 10 for the 1:37 case.

2. For the 1:150 case, 14% of the incoming attic ventilation air that was destined for the upper attic zone, as calculated by the Parker model, was diverted to the lower attic. Twenty-one percent and one hundred percent of the upper attic airflow was diverted to the lower attic for the 1:120 and 1:37 cases, respectively. The rationale was that with increased vent area and flow, the attic should become more mixed. Refer to Rudd (1996) for additional details.

Figure 2 shows a plot of the resulting percent ceiling heat flux reductions, compared to the sealed case, for various levels of attic ventilation area as a percentage of attic floor area. One curve shows a fit of the measured data, while a second curve shows a fit of values predicted by the modified attic model.

RESULTS

Peak Cooling Day, Orlando, Florida

The peak cooing day for Orlando, Florida, using TMY weather data, was 1 August. Figure 3 shows the peak cooling

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TABLE 5
Las Vegas Parametric Simulations

Simulation Number	Input Deck Changes From Reference Case	Research Question Asked
1	1:300 Attic Ventilation	Effect of reducing attic ventilation area from current Las Vegas building code
2	Sealed Attic, R-28 insulation on flat ceiling	Effect of just sealing attic
3	Sealed Attic, R-40 insulation on flat ceiling	Effect of sealing attic and increasing insulation
4	Sealed Attic, R-28 insulation under roof slope	Effect of sealing attic and moving insulation under roof slope (air and thermal barrier at roof plane)
5	Sealed Attic, R-40 insulation under roof slope	Effect of sealing attic and moving insulation under roof slope and increasing insulation
6	Sealed Attic, R-28 insulation under roof slope, White Tile Roof	Effect of sealing attic and moving insulation under roof slope and using white tile on roof
7	White Tile Roof	Effect of white tile roof alone
8	Ducts In Conditioned Space	Effect of placing ducts inside conditioned space (conduction heat transfer effect only, no duct leakage)
9	Duct Leakage, 10% Return Side, 5% Supply Side, (Return leak comes from: 70% attic, 20% garage, 10% outdoors)	Effect of average amount of duct leakage (Based on measurements from 160 Florida homes, the average return side leak was 11% of the total flow, and the estimated average supply side leak was 5% (Cummings 1991))
10	Duct Leakage, 15% Return Side, 10% Supply Side	Effect of greater than average amount of duct leakage

day ceiling heat flux curves. Compared to the sealed attic with flat ceiling insulation, ceiling heat flux reductions of 18% and 27% were predicted for the 1:300 and 1:150 ventilated attics, respectively. Figure 4 illustrates the dramatic increase in cooling power required (about one-third more) for the 1:300 vented attic with 15% duct leakage compared to the 1:300 vented attic without duct leakage (reference case). Relatively little difference in cooling power was seen between the reference vented attic and the sealed cathedralized attic with the same insulation thermal resistance (R-19 h·ft^2·°F/Btu). However, in the late afternoon, the sealed cathedralized attic's cooling power is higher for two hours; it is also slightly less in the late morning. Comparing Figures 5 and 6, one can see that there was almost no difference in shingle temperature between the reference vented 1:300 attic and the 1:150 attic. Referring to Figure 7, peak roof shingle temperatures were within 5°C (9°F) for all black shingle cases, peaking at 84°C (183°F),

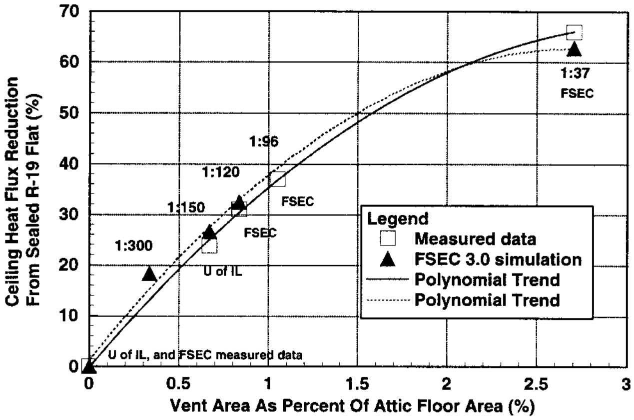

Figure 2 *Measured and predicted ceiling heat flux reduction, as compared to the sealed attic with R-19 flat ceiling insulation.*

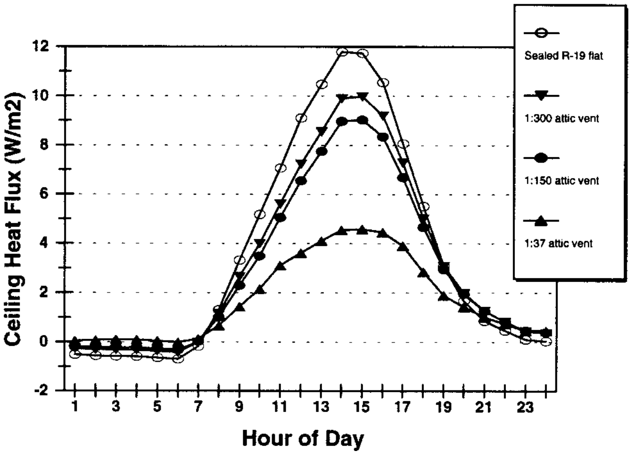

Figure 3 *Orlando peak day ceiling heat flux for the sealed attic, and normal to very large ventilation areas, all with R-19 flat ceiling insulation.*

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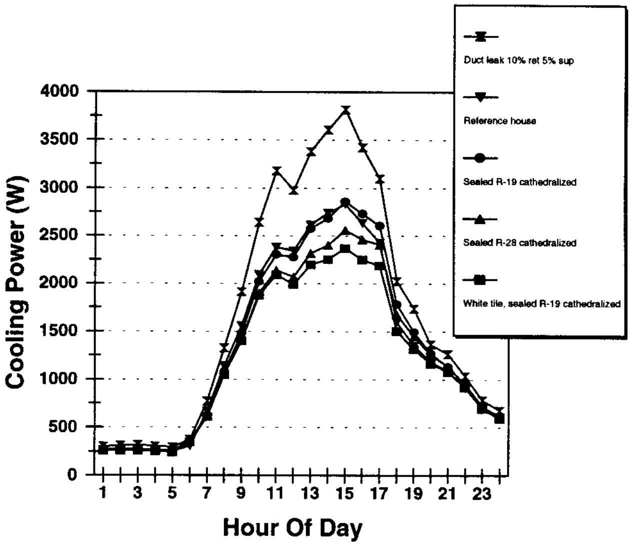

Figure 4 *Orlando peak day cooling system power draw for a vented attic with duct leakage, the reference vented attic, and three variations of the sealed cathedralized attic.*

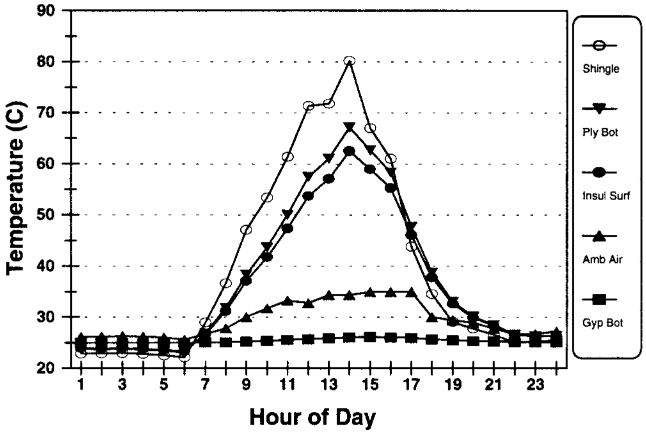

Figure 5 *Orlando peak cooling day temperatures, from roof-top to interior gypsum board, for the reference house (1:300 vented attic, R-19 flat ceiling insulation).*

whether the attics were vented or sealed or whether the insulation was flat or cathedralized. Figure 8 shows the peak cooling day temperature at the bottom (facing the attic) of the roof plywood for several of the parametric simulations. Of primary importance here is that the difference in roof plywood temperature between the 1:300 vented attic case and the sealed attic cases was less than 7°C (13°F). There was about 2°C (4°F) difference in roof plywood temperature between the 1:300 vented attic and the 1:150 vented attic. The effect of white tile was dramatic, dropping roof plywood temperature about 24°C (43°F), with respect to the reference 1:300 vented attic.

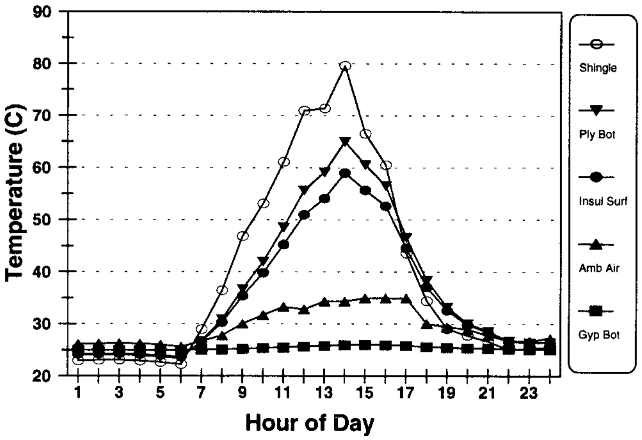

Figure 6 *Orlando peak day temperatures from roof-top to interior gypsum board, for the 1:150 vented attic.*

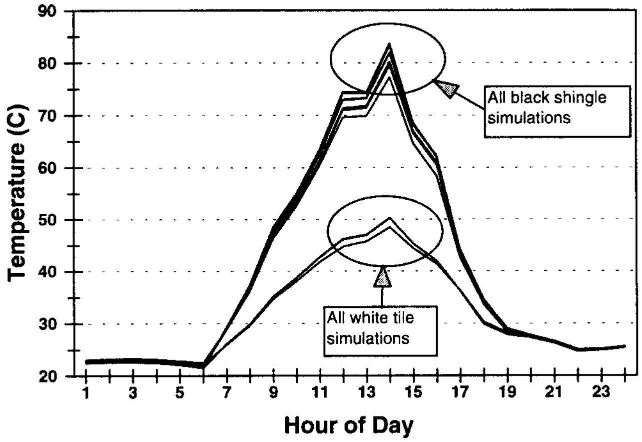

Figure 7 *Orlando peak day top of roof shingle or top of roof tile temperature for all parametric simulations (south side of roof).*

Peak Cooling Day, Las Vegas, Nevada

The peak cooing day for Las Vegas, Nevada, using TMY weather data, was 30 July. Figure 9 shows the peak cooling day ceiling heat flux curves. Compared to the sealed attic with flat ceiling insulation, ceiling heat flux reductions of 14% and 22% were predicted for the 1:300 and 1:150 ventilated attics, respectively. Figure 10 illustrates a 10% increase in peak cooling power required for the 1:150 vented attic with 15% duct leakage compared to either the 1:150 vented attic without duct leakage (reference case) or the 1:300 vented attic without duct leakage. Almost no difference in cooling power was seen between the 1:150 vented attic and the 1:300 vented attic. At most, a 6% difference in cooling power was seen between the reference vented attic and the sealed cathedralized attic with the same insulation thermal resistance (R-28 h·ft^{2}·°F/Btu). From morning through hour 16, the sealed cathedralized attic required as much as 6% less cooling power than the reference

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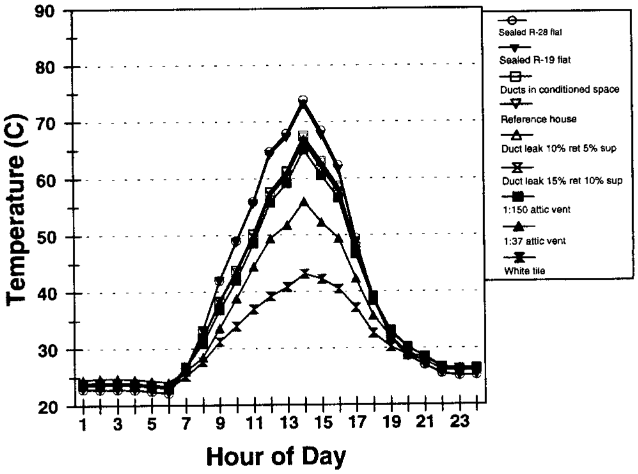

Figure 8 *Orlando peak day bottom-of-roof plywood temperatures (south side).*

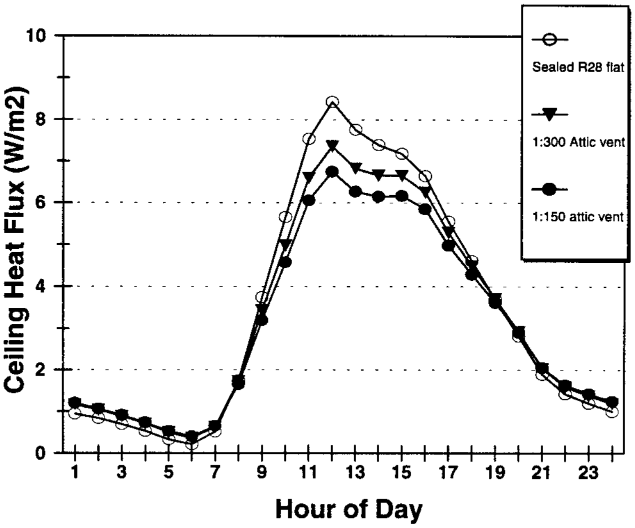

Figure 9 *Las Vegas peak cooling day ceiling heat flux for sealed and normally vented attics, all with R-28 flat ceiling insulation.*

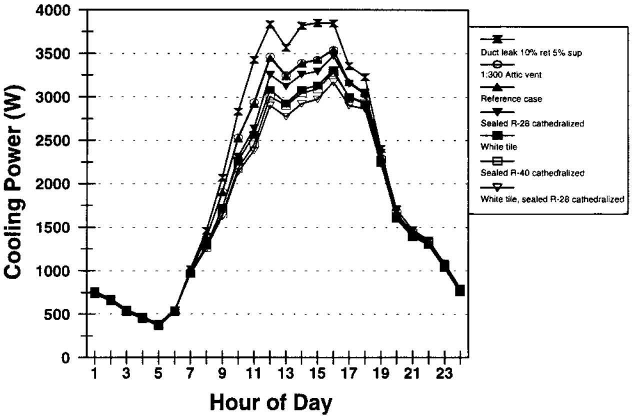

Figure 10 *Las Vegas peak day cooling system power draw for a 1:150 vented attic with duct leakage, a 1:300 vented attic, the reference 1:150 vented attic, white tile roof, and three variations of the sealed cathedralized attic.*

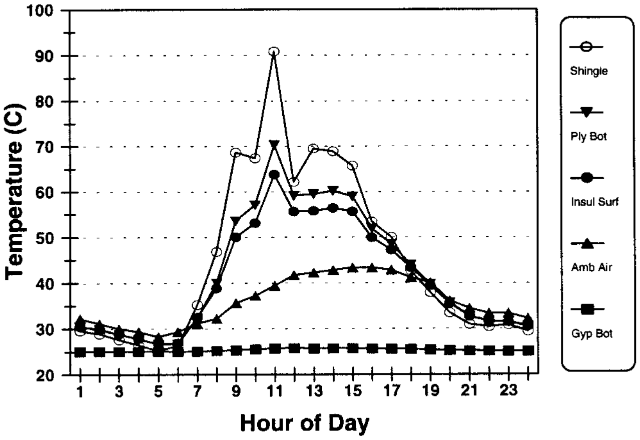

Figure 11 *Las Vegas peak cooling day temperatures, from rooftop to interior gypsum board, for the reference house (1:150 vented attic, R-28 flat ceiling insulation.*

vented attic; after hour 16 the cooling power requirement was essentially the same. Using white tile or using R-40 insulation in the sealed cathedralized attic lowered the cooling power even more, and each had essentially the same effect. Comparing Figures 11 and 12, one can see that there was almost no difference in shingle temperature between the reference vented 1:300 attic and the 1:150 attic. Referring to Figure 13, peak roof shingle temperatures were within 4°C (7°F) for all black shingle cases, peaking at 92°C (198°F), whether the attics were vented or sealed or whether the insulation was flat or cathedralized. Figure 14 shows the peak cooling day temperature at the bottom (facing the attic) of the roof plywood for several of the parametric simulations. Of primary importance here is that the difference in roof plywood temperature between the 1:300 vented attic case and the sealed attic cases was less than 8°C (14°F). There was less than 3°C (5°F) difference in roof plywood temperature between the 1:300 vented attic and the 1:150 vented attic. The effect of white tile was dramatic, dropping roof plywood temperature about 23°C (41°F) with respect to the reference 1:150 vented attic.

Annual Simulations, Orlando, Florida

Orlando annual simulation results are given in Tables 6 and 7. Results showed that, compared to the reference vented attic, with no duct leakage, the sealed cathedralized attic (i.e., sealed attic with the air barrier and thermal barrier [insulation] at the sloped roof plane) could save 2% on space conditioning energy. With the reference case R-5 ($h{\cdot}ft^2{\cdot}°F/Btu$) duct insulation and no duct leakage, simply moving the air distribution ducts inside conditioned space could save 3% annually. Thus,

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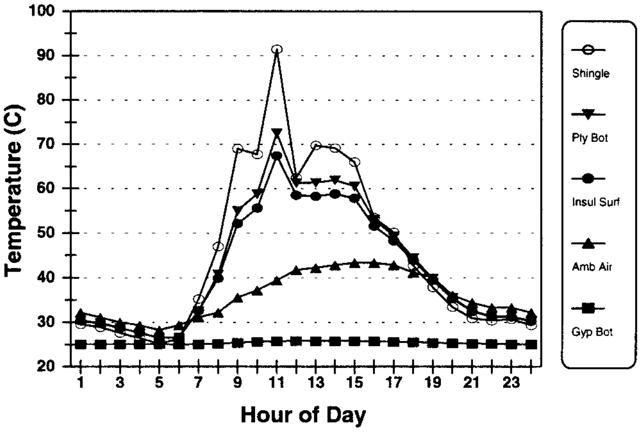

Figure 12 *Las Vegas peak cooling day temperatures, from rooftop to interior gypsum board, for the 1:300 vented attic.*

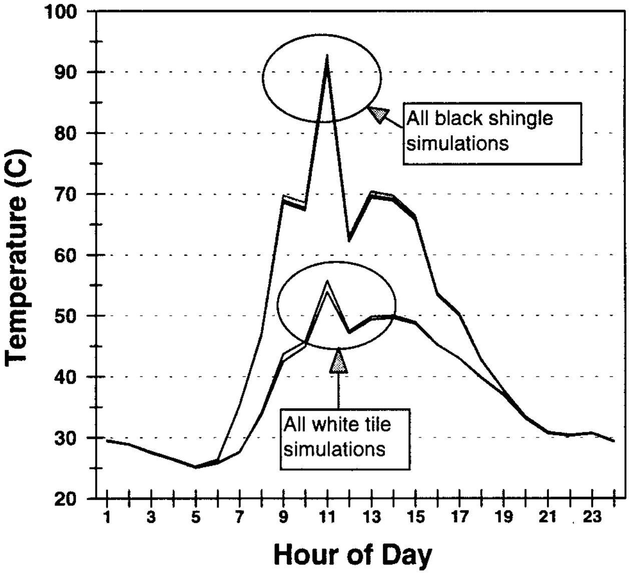

Figure 13 *Las Vegas peak cooling day top of roof shingle or roof tile temperature for all parametric simulations (south side of roof).*

excluding the location of ducts, the annual net effect of sealing the attic and moving the insulation from the flat ceiling to under the sloped roof is less than 1%. When typical duct leakage was modeled (10% return leak, 5% supply leak), the peak cooling load increased by 42% and the sealed cathedralized attic showed annual space conditioning savings of 16%.

Simply sealing the attic, without moving the insulation directly under the roof sheathing, could increase annual space conditioning energy use by a maximum of 6%. A lower shingle absorptivity would produce a lower penalty. However, if attic moisture condensation was a problem in existing housing in the Orlando climate, sealing the attic could be a solution to the attic condensation problem, and increasing the flat ceiling

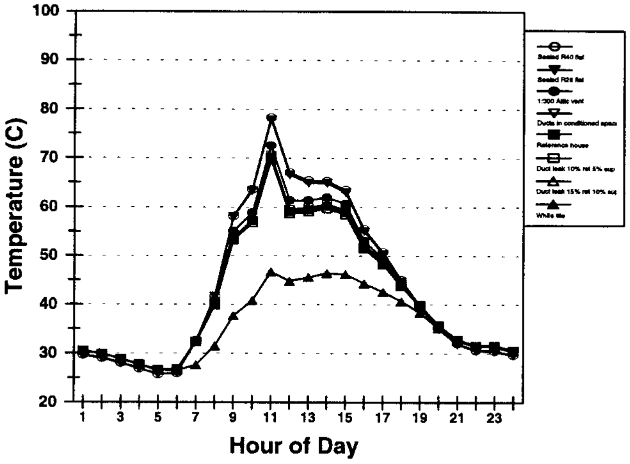

Figure 14 *Las Vegas peak cooling day bottom-of-plywood temperatures (south side of roof).*

insulation from R-19 to R-28 nearly mitigates the space conditioning energy use penalty.

Increasing the attic vent area from 1:300 to 1:150 had less than a 1% annual net effect (–1.3% cooling, +0.8% heating). The use of white roof tile instead of black shingles could save 6% on annual space conditioning energy use in Orlando. A peak cooling load reduction of 13% was shown when simulating white roof tile versus black shingles. The combination of white roof tile and the sealed cathedralized attic, compared to black shingles and vented attic, could save 12% on annual space conditioning energy use in Orlando.

Annual Simulations, Las Vegas, Nevada

Las Vegas annual simulation results are given in Tables 8 and 9. Results showed that, compared to the reference vented attic, with no duct leakage, the sealed "cathedralized" attic (i.e., sealed attic with the air barrier and thermal barrier [insulation] at the sloped roof plane) could save 4% on space conditioning energy. With the reference case R-5 (h·ft^2·°F/Btu) duct insulation and no duct leakage, simply moving the air distribution ducts inside conditioned space could save 4% annually. Thus, excluding the location of ducts, there is no annual net effect of sealing the attic and moving the insulation from the flat ceiling to under the sloped roof in the Las Vegas climate. When typical duct leakage was modeled (10% return leak, 5% supply leak), the peak cooling load increased by 23% and the sealed cathedralized attic showed annual space conditioning savings of 10%.

Simply sealing the attic, without moving the insulation directly under the roof sheathing, could increase annual space conditioning energy use by a maximum of 6%. A lower shingle absorptivity would produce a lower penalty. Increasing the flat ceiling insulation from R-28 to R-40 nearly mitigates the space conditioning energy use penalty.

Decreasing the attic vent area from 1:150 to 1:300 had less than a 1% effect on heating or cooling and had no annual net effect on space conditioning energy use. The use of white

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TABLE 6
Summary of Annual Simulation Results for Orlando

Orlando, Florida **Simulation Description**	**Annual Cooling kW·h**	**Diff. %**	**Annual Heating kW·h**	**Diff. %**	**Annual Total kW·h**	**Diff. %**	**Peak Cooling kW**	**Diff. %**	**Peak Heating kW**	**Diff. %**
Reference case	**4419**		**2193**		**6613**		**1.56**		**1.44**	
White tile, sealed R-28 sloped	3891	-12.0	1904	-13.2	5795	-12.4	1.29	-17.3	1.31	-9.0
Sealed R-28 sloped	4261	-3.6	1793	-18.2	6055	-8.4	1.41	-9.6	1.30	-9.7
White tile, sealed R-19 sloped	3948	-10.7	2142	-2.3	6090	-7.9	1.34	-14.1	1.38	-4.2
White tile	3971	-10.2	2270	3.5	6241	-5.6	1.36	-12.8	1.44	0.0
Ducts in conditioned space	4324	-2.2	2103	-4.1	6427	-2.8	1.46	-6.4	1.34	-6.9
Sealed R-19 sloped	4467	1.1	2002	-8.7	6469	-2.2	1.57	0.6	1.38	-4.2
1:150 attic vent	4364	-1.3	2211	0.8	6575	-0.6	1.53	-1.9	1.46	1.4
Sealed R-28 flat	4531	2.5	2120	-3.3	6651	0.6	1.67	7.1	1.48	2.8
Sealed R-19 flat	4713	6.6	2316	5.6	7029	6.3	1.80	15.4	1.54	6.9
Duct leak 10% ret 5% sup	5058	14.4	2596	18.4	7654	15.7	2.21	41.7	1.81	25.7
Duct leak 15% ret 10% sup	5428	22.8	2895	32.0	8323	25.9	2.71	73.7	2.03	41.0

TABLE 7
Observations of Annual Simulation Results for Orlando

Orlando, Florida	
Simulation Description	**Observations Of Results**
Reference case	*(R-19 ceiling, 1:300 vented attic, ducts in attic, no duct leakage, R-11 walls, single glazing)*
White tile, sealed R-28 sloped	Excellent for cooling and heating
Sealed R-28 sloped	Good for cooling, excel. for heating, excel. for balanced peak load reduction if using heat pump
White tile, sealed R-19 sloped	Excellent for cooling, good for heating
White tile	Excellent for cooling, penalty for heating due to loss of solar gains, net positive benefit
Ducts in conditioned space	Always good
Sealed R-19 sloped	Small penalty for cooling, good for heating, better overall than reference case, essentially the same as placing ducts in conditioned space or 1:37 attic ventilation
1:150 attic vent	Very little net difference from 1:300 reference case
Sealed R-28 flat	Penalty on cooling, saves on heating, nets essentially the same as reference case
Sealed R-19 flat	Energy use penalty – but excludes moisture laden outside air
Duct leak 10% ret 5% sup	Never good
Duct leak 15% ret 10% sup	Never good

roof tile instead of black shingles could save 2% on annual space conditioning energy use in Las Vegas. Peak cooling load reduction of 6% was shown when simulating white roof tile vs. black shingles. The combination of white roof tile and the sealed cathedralized attic, compared to black shingles and vented attic, could save 5% on annual space conditioning energy use in Las Vegas.

CONCLUSION

A residential attic model (Parker et al. 1991), contained in the finite element computer program FSEC 3.0, was empirically aligned with measured attic data from three roof research facilities in Florida and Illinois. This model was then used to

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TABLE 8
Summary of Annual Simulation Results for Las Vegas

Las Vegas, Nevada **Simulation Description**	**Annual Cooling kW·h**	**Diff. %**	**Annual Heating kW·h**	**Diff. %**	**Annual Total kW·h**	**Diff. %**	**Peak Cooling kW**	**Diff. %**	**Peak Heating kW**	**Diff. %**
Reference case	4062		6502		10565		1.94		1.51	
Sealed R-40 sloped	3858	-5.0	5761	-11.4	9619	-8.9	1.78	-8.2	1.40	-7.3
White tile, sealed R-28 sloped	3611	-11.1	6455	-0.7	10066	-4.7	1.73	-10.8	1.46	-3.3
Ducts in conditioned space	3879	-4.5	6243	-4.0	10121	-4.2	1.77	-8.8	1.44	-4.6
Sealed R-28 sloped	4075	0.3	6107	-6.1	10182	-3.6	1.88	-3.1	1.46	-3.3
White tile	3697	-9.0	6669	2.6	10366	-1.9	1.83	-5.7	1.52	0.7
1:300 Attic vent	4096	0.8	6449	-0.8	10545	-0.2	1.94	0.0	1.50	-0.7
Sealed R-40 flat	4261	4.9	6329	-2.7	10590	0.2	2.12	9.3	1.53	1.3
Sealed R-28 flat	4454	9.7	6689	2.9	11144	5.5	2.31	19.1	1.58	4.6
Duct leak 10% ret 5% sup	4399	8.3	7169	10.2	11567	9.5	2.39	23.2	1.95	29.1
Duct leak 15% ret 10% sup	4643	14.3	7649	17.6	12292	16.4	2.62	35.1	2.52	66.9

TABLE 9
Observations of Annual Simulation Results for Las Vegas

Las Vegas, Nevada	
Simulation Description	**Observations Of Results**
Reference case	*(R-28 ceiling, 1:150 vented attic, ducts in attic, no duct leakage, R-19 walls, double glazing)*
Sealed R-40 sloped	Good for cooling, excellent for heating
White tile, sealed R-28 sloped	Excellent for cooling, no difference for heating
Ducts in conditioned space	Always good
Sealed R-28 sloped	No difference for cooling, very good for heating
White tile	Very good for cooling, penalty for heating due to reduced solar heat gain
1:300 Attic vent	Very little net difference from 1:150 reference case
Sealed R-40 flat	Penalty on cooling, saves on heating, nets essentially the same as reference case
Sealed R-28 flat	Not recommended
Duct leak 10% ret 5% sup	Never good
Duct leak 15% ret 10% sup	Never good

simulate hourly space conditioning energy use and roof and attic temperatures for peak cooling days and annual weather for Orlando, Florida, and Las Vegas, Nevada.

Results showed that, when compared to typically vented attics with the air distribution ducts present, sealed “cathedralized” attics (i.e., sealed attic with the air barrier and thermal barrier [insulation] at the sloped roof plane) can be constructed without an associated energy penalty in hot climates.

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