Improving Attic Thermal Performance

With metal roofing systems becoming more popular for new construction and retrofits, the Florida Solar Energy Center wanted to learn more about these roofing systems and their effect on thermal performance.

by Danny Parker

For homes in hot climates, roofing systems and attic thermal performance have a heavy impact on cooling energy use. Using insulation to control the heat flux from the attic into conditioned spaces through the ceiling is a known way to increase an attic's thermal performance, but there are other problems that need to be dealt with. There is heat gain to the thermal distribution system when ducts are located in the attic. Also, leaky supply ducts can cause negative pressures within the house when the air handler is on. The negative pressures can cause hot air from the attic to be drawn into the conditioned space through gaps around recessed light fixtures or other bypasses, adding further to the home's cooling load (see Figure 1).

With metal roofing systems becoming more popular for new construction and re-roofing, the Florida Solar Energy Center (FSEC) wanted to learn more about these roofing systems, and about their effect on attic temperature. And we were curious to find out how well metal roofing systems performed compared to traditional black-shingle roofing systems. During the summer of 2002, we performed testing on four finished and unfinished metal roofing systems and two roofing systems using traditional dark asphalt shingles. Our research shows that controlling attic air temperatures can be just as important as reducing ceiling heat flux during times of peak cooling loads (see "Not So Extreme Attic Example," p. 14). We found that the metal roofing systems we tested generally perform well, although the performance of some of them degrades over time.

FSEC

FSEC's Flexible Roof Facility allows side-by-side testing of different roof configurations.

Side-by-Side Roof Testing

The experiments took place at our Flexible Roof Facility (FRF) in Cocoa, Florida. The FRF is a 24 ft x 48 ft frame building constructed with its long axis oriented east-west (see photo above). The roof and attic are partitioned to allow simultaneous testing of multiple roof configurations. The attic is sectioned into six 6-ft-wide test cells that are thermally separated by partitions. The partitions between the individual cells are well sealed to prevent air flow between cells and are insulated to R-20 using 3 inches of isocyanurate insulation. The gable roof has a $^{5}/_{12}$ pitch and $^{3}/_{4}$-inch plywood decking. With the exception of cell 2, R-19 unsurfaced batt insulation is installed in a consistent fashion between the attic trusses in the test bays. The attic is separated from the conditioned interior by $^{1}/_{2}$-inch gypsum board. The interior of the FRF is a single air-conditioned space.

The facility allows reconfiguration with different roofing products, and we've used it to examine different levels of ventilation and installation configurations for tile roofing. We've also compared reflective roofing, radiant barriers, and sealed attic construction. Our recent testing addressed several questions. (Note that 1:300 ventilation is 1 ft^2 of attic ventilation, or net free vent area, per 300 ft^2 of attic floor area.)

- What is the performance (ceiling flux and attic air temperatures) of a standard black asphalt shingle roof with 1:300 ventilation (the control cell)?
- How does the Galvalume metal roof compare in thermal performance with a galvanized metal roof?
- How does an ivory metal shingle roof perform compared with the roof

Table. Tested Roofing Material Solar Reflectances and Emittances

Description	Solar Reflectance (%)	Long-Wave Emittance
Cell 1: Galvalume unfinished 5-vee metal	64.6	0.28
Cell 2: Black shingle	2.7	0.90
Cell 3: IR reflective ivory metal shingle	42.8	0.83
Cell 4: Galvanized unfinished 5-vee metal	70.9	0.04
Cell 5: Black shingle	2.7	0.90
Cell 6: White metal standing seam	67.6	0.83

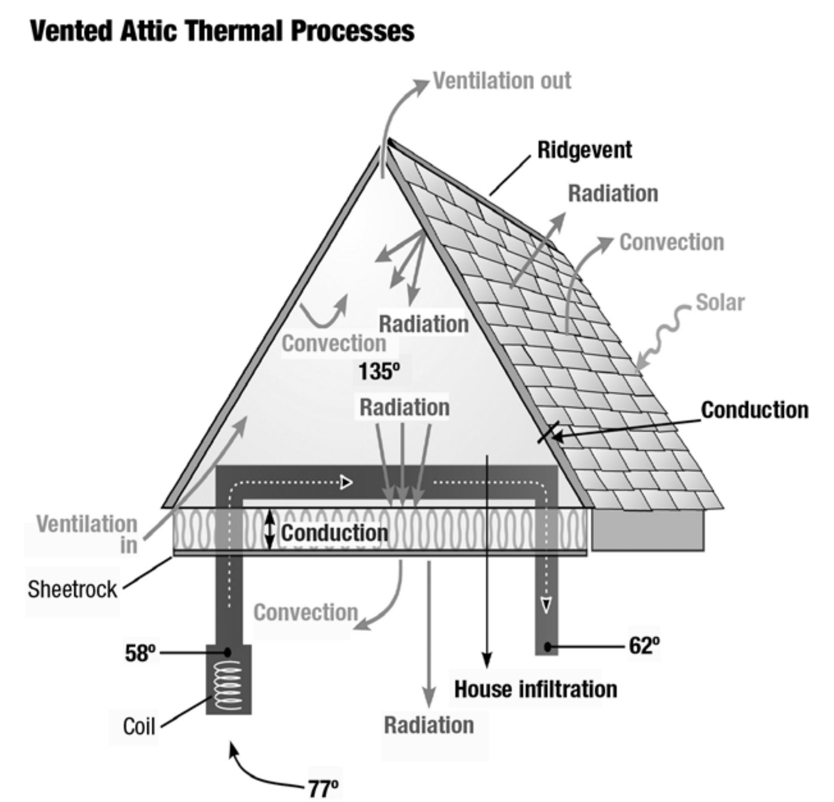

Figure 1. Using insulation to control the heat flux from the attic into conditioned spaces through the ceiling is a known way to increase an attic's thermal performance, but there are other problems that need to be dealt with.

with a lower solar reflectance that was installed the previous summer?

• How does an innovative double roof construction with an insulated roof deck, radiant barrier, and no attic ventilation perform compared with other types?

• How does a white standing-seam metal roof perform compared with an unfinished metal roof?

We used six different test configurations. (All the vented cells have soffit and ridge venting.)

Cell 1. A Galvalume 5-vee unfinished metal roof with a 1:300 vented attic (1st year tested).

Cell 2. Black asphalt shingles with a vented double roof deck, a radiant barrier, 6-inch foam insulation on the underside of the bottom roof deck, and an unvented attic (2nd year tested).

Cell 3. Solar-reflective ivory metal shingles with a 1:300 soffit and ridge ventilation (1st year tested).

Cell 4. A galvanized 5-vee unfinished metal roof with 1:300 ventilation (1st year tested).

Cell 5. Black asphalt shingles with a 1:300 soffit and ridge ventilation. This configuration has been installed for 15 years and is the control cell.

Cell 6. A white standing-seam metal roof with a 1:300 vented attic (7th year tested).

All the roofing materials were installed in a conventional manner according to the manufacturers' specifications.

We tested samples of the new unexposed roofing materials to establish their solar reflectance and long-wave emittance (see Table). There is a large difference in the long-wave emittance of the two unfinished metal roofs. The emittance of Galvalume (0.28) is much lower than that of the painted metal roof (0.83), but the emittance of the unfinished galvanized roof is much lower still (0.04). Generally, low emissive surfaces reach higher temperatures than high emissive surfaces since low emissive surfaces absorb more solar radiation and do not readily give up collected heat back to the sky or to their surroundings.

Using precision thermocouples, we made a number of temperature measurements at the exterior surface of the roof and the underlayment; at the underside of the deck; in attic air at several heights within the attic; in the soffit inlet air and ridge vent exit air; at the top surface of the insulation; and at the interior ceiling of the conditioned space. The outside air temperature, insolation, humidity, and rainfall were also measured. All of the test cells were monitored from June 5 to September 30, 2002.

Test Results

To find differences in space cooling, we evaluated the different roof systems to examine attic temperatures, heat flux through the ceiling into the conditioned space below, and the overall impacts of the thermal differences of the roofing system on required air conditioning.

Attic Air Temperatures

Controlling attic air temperatures is important, since the time when the attic becomes hottest—late afternoon—is almost always the time when the A/C runs the most and gains to the duct system are increased. The average summer day midattic air temperature profiles show the impact of the roofing options in reducing attic air temperatures and cooling energy use associated with attic duct heat gains and loads from unintended air leakage coming from the attic zone (see Figure 2). The statistics for the average, minimum, and maximum midattic air temperatures over the entire summer show that the sealed attic with the double roof provides the lowest overall mean attic temperatures (77.7ºF) and hence the lowest attic duct system heat gains and impact from return air leakage from the attic.

The next most productive roof combination in this regard is cell 6 with the vented white metal roof (81ºF). Cell 3, with the IR reflective metal shingle roof, had a very similar performance (82.2ºF). Next best in performance is cell 1, with the Galvalume metal roof and the vented attic at 83.6ºF. The low-emissivity galvanized metal roof (cell 4) was the least effective of the metal roof systems. Cell 4 attic temperature averaged 85.1ºF compared with the standard attic, which averaged 89.1ºF.

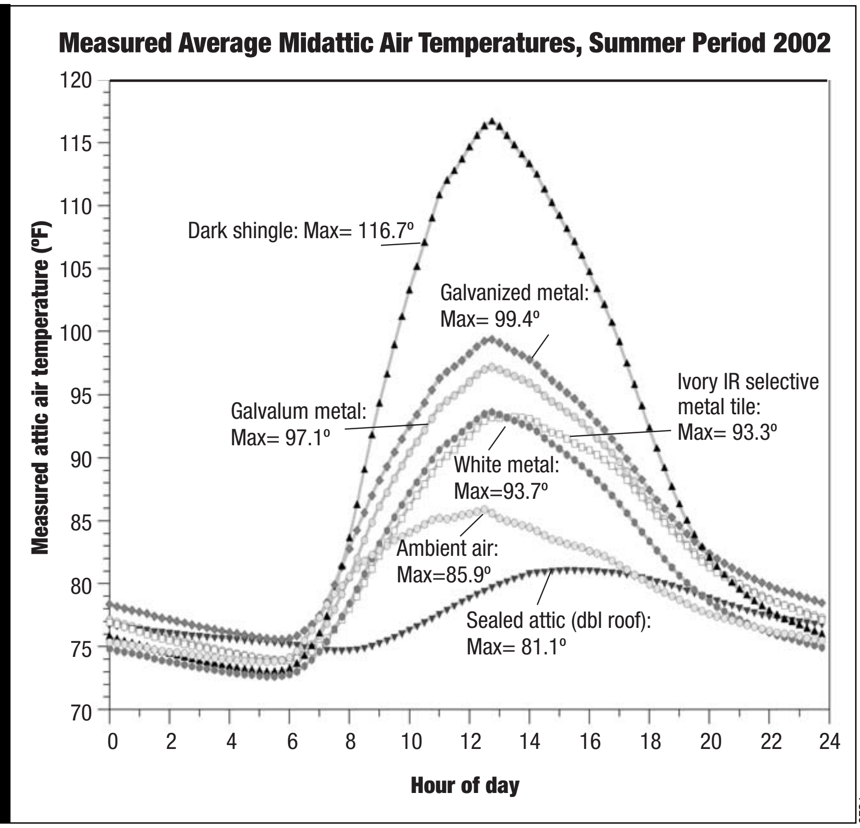

Figure 2. The average summer day midattic air temperature profiles show the impact of the roofing options in reducing attic air temperatures and cooling energy use.

Maximum Attic Air Temperatures

We compared the average daily maximum midattic air temperature for each cell against the average daily maximum ambient air temperature along with the corresponding temperature difference for the full summer period. These results show the success of the various roofing options in controlling duct heat gains and loads from unintended air leakage under peak conditions for the period.

Note that cell 2, with the sealed attic and insulation on the underside of the roof decking cannot be directly compared with the other cells, because the other cells do not have roof deck insulation; instead, they have insulation on top of the ceiling. However, when we compared the 2002 summer results with the 1999 and 2000 cell 2 results (sealed attic without double roof deck and radiant barrier), we found that the average maximum midattic temperature difference from ambient was 4.7ºF lower for the double roof/radiant barrier combination than it was for the same sealed attic without the double roof. The maximum midattic temperature for the double roof deck and radiant barrier was 81.1ºF, or 7.1ºF lower than the averaged 1999 and 2000

Not So Extreme Attic Example

Here is a simple illustration of the effect of a roof system on cooling needs. Assume a 2,000 ft^2 ceiling with R-30 attic insulation. Supply ducts typically comprise approximately 25% of the floor area, but they are only insulated to between R-4 and R-6. With the peak attic temperature at 130ºF, and 78ºF maintained inside the house, a UA ΔT calculation shows a ceiling heat gain of 3,500 Btu per hour. With R-5 ducts in the attic and a 57ºF supply air temperature, the heat gain to the duct system is 7,300 Btu per hour—twice the ceiling flux.

This is aggravated by the location of the air handler within the attic space—a common practice in much of the southern United States, but particularly in Texas and California. The air handler is poorly insulated but it has the greatest temperature difference at the evaporator of any location in the cooling system. It also has the greatest negative pressure just before the fan, so that some leakage into the unit is inevitable. As evidence for this influence, a monitoring study of air conditioning energy use in 48 central Florida homes found that homes with the air handlers located in the attic used 30% more space cooling energy than those with air handlers located elsewhere.

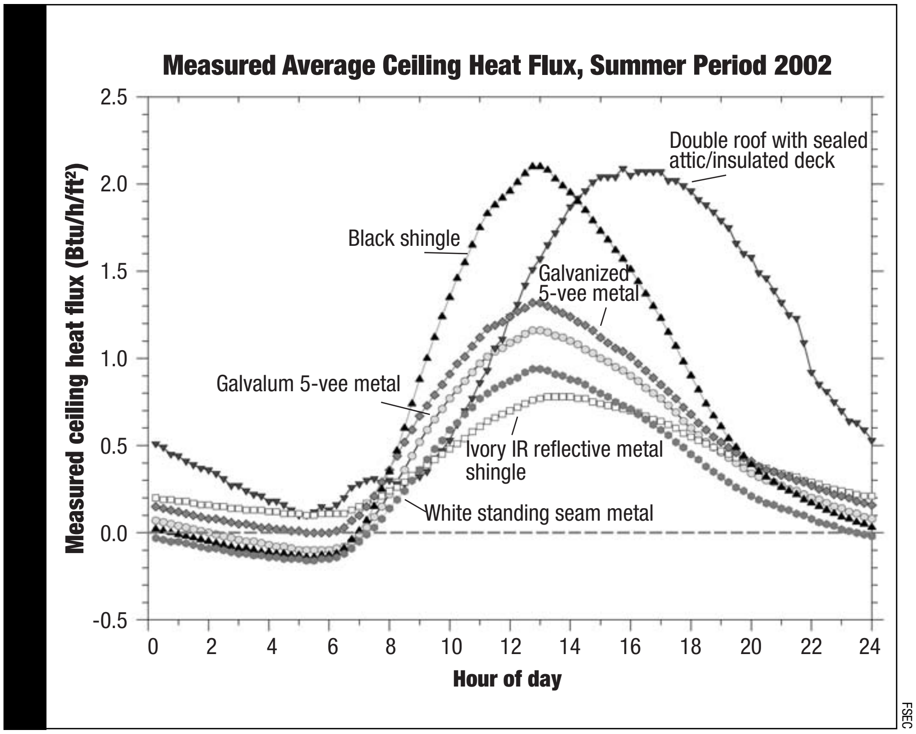

Figure 3. The double roof showed both the lowest mean and peak attic air temperatures of the group, and the highest ceiling heat flux. This seemingly contradictory result stems from the fact that the floor of the sealed attic (which forms the ceiling of the conditioned zone) is not insulated, so that the attic is unintentionally conditioned.

results. The outdoor temperatures were quite similar during the two years in Florida's predictably hot summers.

The high-reflectance ivory metal shingle (cell 3) provided the coolest attic of the test cells without roof deck insulation. The average maximum midattic temperature in this case was 93.3°F, or 7.4°F higher than ambient. In 2001, the brown, IR reflective shingle on the test cell had a maximum attic air temperature that was 10.6°F higher than ambient. In 2000, the brown (not-high reflectance) metal shingle that was on the same cell had an average maximum attic temperature 13.5°F higher than ambient, while in 1999, a white high-reflectance metal shingle on the same cell had an average maximum attic temperature 3.8°F higher than ambient. Thus, the new ivory colored IR reflective shingle is better than all the tested metal tile products except the white standing-seam metal roof.

The white standing-seam metal roof (cell 6) was cleaned prior to the test for comparison with the pristine Galvalume and galvanized metal roofs. Comparison with the previous year shows the benefits of the cleaning and venting. In 2001, the average daily maximum attic air temperature above ambient was +14.4°F, as compared to +7.8°F in the summer of 2002.

Ceiling Heat Flux

The uninsulated ceiling of the double roof with sealed attic (cell 2) has a peak heat flux similar to that of the control (cell 5), although with a significant time lag of over 3 hours (see Figure 3). The mean heat flux for the double roof is 0.98 Btu/ft^2 per hour, or 40% higher than the control. The double roof showed both the lowest mean and peak attic air temperatures of the group, and the highest ceiling heat flux. This seemingly contradictory result stems from the fact that the floor of the sealed attic (which forms the ceiling of the conditioned zone) is not insulated, so that the attic is unintentionally conditioned—reducing the attic temperatures by increasing heat transfer to the interior space. The absence of insulation on the attic floor produces the high heat fluxes to the interior.

The high reflectance ivory metal shingle roof (cell 3) has the lowest peak ceiling heat flux at 1.19 Btu/ft^2 per hour. It also has a relatively low mean flux of 0.39 Btu/ft^2 per hour, which is slightly higher than the mean flux for the white metal roof at 0.30 Btu/ft^2 per hour. The vented white metal roof shows the lowest overall average heat flux and thus the lowest indicated ceiling influence on cooling for the overall period. The Galvalume roof (mean heat flux of 0.43 Btu/ft^2 per hour) performs similarly to the IR reflective roof. The galvanized metal roof has poorer performance (mean = 0.53 Btu/ft^2 per hour).

Overall Impact of Roofing System

The impact of roofing on cooling energy typically depends on three factors. These are the ceiling heat flux to the interior from the attic, the heat gain to the duct system located in the attic space, and the air unintentionally drawn from the attic into conditioned space. The heat flux through the ceiling impacts the interior temperature and hence the thermostat, which then calls for mechanical cooling. Thus, the heat flux affects cooling energy use at all hours, as well as the demand for air conditioning.

The other two influences—air leakage drawn from the attic into the conditioned space and heat gain to the duct system—usually occur only when the cooling system operates. Thus, the impact depends on the air conditioner run time in a particular time interval, and also on the leakiness of the duct, and on the amount of duct insulation. To obtain the average cooling system run time, we used a large set of residential cooling energy use data. These data come from 171 homes in the central Florida area, where the 15-minute air conditioner power was measured for over a year.

For each site, the maximum demand during summer was also recorded to determine the maximum cooling system power. Thus, it was possible to determine the diversified run time fraction by dividing the average air conditioner system power by its maximum demand. This calculation was made by averaging the air conditioner and air handler power for all sites and dividing by the average maximum summer demand, which was 3.96 kW.

The average cooling system run time is at its maximum (approximately 55%) at 4 pm (same as system diversity) and is at its minimum of (15%) at 6 am. It is important to note that these figures are based on an average summer day, as determined by evaluating all data from June 5 to September 30 inclusive. They do not represent extreme summer day conditions.

To estimate the impact of each roofing system on attic temperature, we assume a typical single-story home with 2,000 ft² of conditioned floor area (see Figures 4 and 5). All of the alternative test cells do better than the control cell. The white metal roof with ventilation (cell 6) does best, followed by the high-reflectance metal shingle roof (cell 3). The Galvalume metal roof with a ventilated attic provides about a 30% reduction in heat gain. The galvanized roof with its significantly lower emissivity, provides only about a 20% heat reduction. The sealed attic with the double roof—cell 5—provides the lowest reduction in daily heat gain. This is primarily a result of the much greater measured heat flux across the uninsulated ceiling in this configuration.

Long-Term Performance

As described earlier, we expect the unfinished galvanized steel roofing products to maintain their reflectance and emissivity properties less well over the long term than the Galvalume product. This is because the Galvalume's aluminum-zinc alloy resists corrosion better. The preliminary data verify this expectation. We compared the maximum average daily attic air temperature for the summers of 2003 and 2002, looking at three types of metal roofing—white standing seam, galvanized, and Galvalume—and standard black asphalt shingle (see Figure 6). While the average maximum

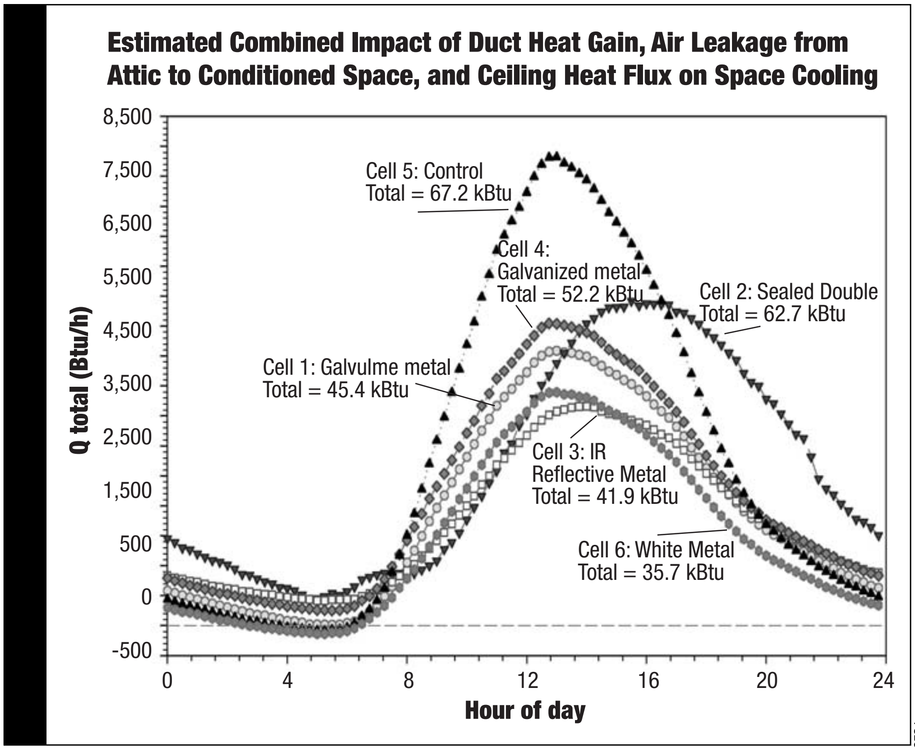

Figure 4. To estimate the impact of each roofing system on attic temperature, we assume a typical single-story home with 2,000 ft² of conditioned floor area. All of the alternative test cells do better than the control cell.

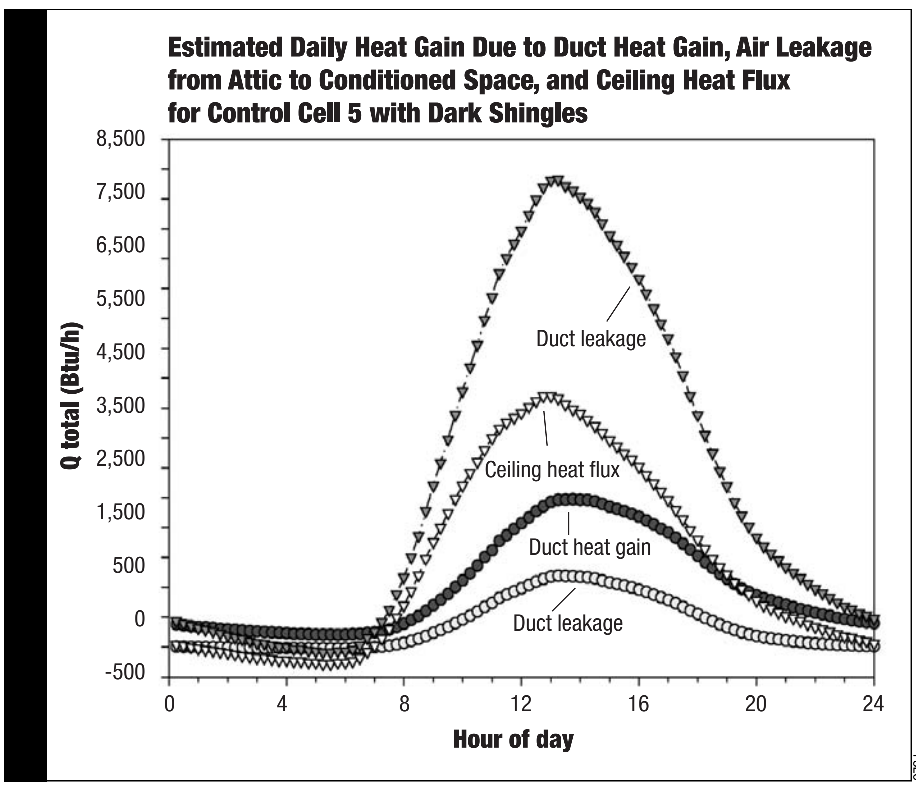

Figure 5. The sealed attic with the double roof—cell 5—provides the lowest reduction in daily heat gain. This is primarily a result of the much greater measured heat flux across the uninsulated ceiling in this configuration.

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Roofers install unfinished metal roofing on the Flexible Roof Facility.

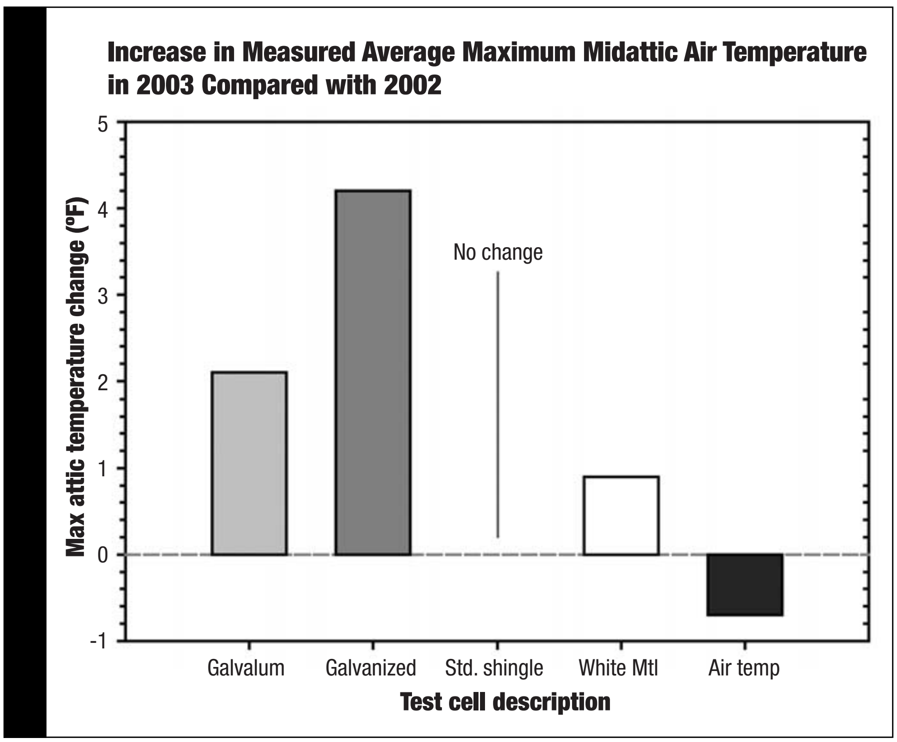

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Figure 6. We expect the unfinished galvanized steel roofing products to maintain their reflectance and emissivity properties less well over the long term than the Galvalume product. The preliminary data verify this expectation.

outdoor air temperature was 0.7°F cooler, we found that each product showed some signs of weathering and increased solar absorptance, resulting in attic heating.

The average maximum attic air temperature under the standard black shingle roof showed no change; it was 116.7°F in both years. However, the average maximum attic air temperature under the galvanized metal roof was 4.2°F hotter in 2003 than in 2002. The average maximum attic air temperature under the Galvalume roof was 2.1°F hotter in 2003, while the white metal roof showed an average increase of only 0.9°F. Note that white metal remained the best choice with Galvalume next. This is consistent with anecdotal observation (Tennessee Williams's *Cat on a Hot Tin Roof*). After additional years of exposure, we expect that the Galvalume and galvanized will differ more widely in thermal performance. We expect that Galvalume will better maintain its performance, with most weathering occurring within the first year. This is because its surface properties are tailored to maintain its reflectance and weather resistance. The white metal roof was weathered in the sense that it accumulated dust and dirt, but there were no changes to the surface characteristics caused by oxidation. The white metal roof also showed the lowest degradation of the three metal roofs. Within the project, performance is being monitored for a third year in the same configuration to examine any further changes due to weathering.

Ranking the Roofs

Our test results from the summer of 2002 allowed us to compare the relative thermal performance of finished and unfinished metal roofing systems under typical Florida summer conditions (see Figure 7). The vented standing-seam white metal roof had the lowest total system heat gain of all the tested roofs, since its ceiling heat flux was much lower than that for roofs with the sealed attic construction. Its attic temperatures were also much lower than those for the standard black shingle control cell. The average daily maximum attic temperature was only about 94°F. Cooling-related savings were on the order of 47% of roof-related heat gain.

The sealed attic double roof system (cell 2) provided the coolest attic space of all systems tested (average maximum daily midattic temperature was 81.1°F), and therefore also the lowest estimated duct leakage and duct conduction heat gains. However, it also had the highest ceiling heat flux of all systems tested, due to the fact that the ceiling was uninsulated. This reduced its improvement over the standard black shingle roof in the control cell to a modest 7% savings in roof-related cooling energy. Note also that since this double roof configuration provided significantly cooler attic temperatures than the standard sealed attic tested during the previous two summers, higher total heat gains should be anticipated from standard sealed attics. Of course, it would be possible to combine both technologies—a cool roof and sealed attic construction—to produce even better results than any shown here. This suggests an area for future research.

A major objective of the testing was to evaluate popular unfinished metal roofing systems. We tested an unfinished Galvalume 5-vee metal roof with attic ventilation as well as a galvanized 5-vee metal roof in an identical configuration. The galvanized roof has a high solar reflectance, but a much lower long-wave emittance than the Galvalume roof (0.04 versus 0.28 for the Galvalume), which we expected to hurt its performance. The monitoring bore out this expectation. The Galvalume metal roof ran cooler than the galvanized system and produced less roof-related heat gain. The Galvalume roof provided a 32% reduction in roof and attic-related heat gain over the summer as compared with a 22% reduction for the galvanized roof. Moreover, as galvanized roofs are known to lose their solar reflectance rapidly over time as the zinc surface oxidizes, we expect to see a further decrease in performance in future seasons of testing. Although white metal performs best, the Galvalume metal roofing surface is a good second choice for cooling related climates, and does nearly as well as the IR selective ivory metal shingles.

At an average maximum midattic temperature of 93.3°F (23.4°F lower than the black shingle control cell), the high reflectance ivory metal shingle roof (cell 3) provided the coolest peak attic temperature of all the cells without a double roof deck. While its reflectance was somewhat lower than

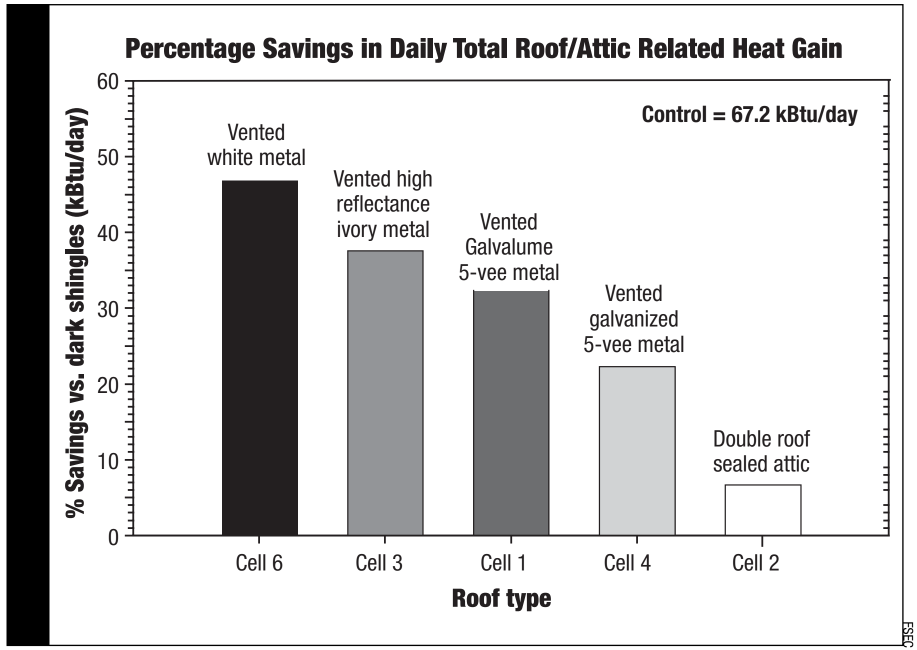

Figure 7. The vented standing-seam white metal roof had the lowest total system heat gain of all the tested roofs, since its ceiling heat flux was much lower than that for roofs with the sealed attic construction.

that of the white metal roof, the air space under the metal shingles provides additional effective insulation. Both of these characteristics probably come into play to help the high-reflectance roof achieve lower peak attic temperatures, while the additional insulating effect explains its slightly higher nighttime attic temperatures.

We also estimated the combined impact of ceiling heat flux, duct heat gain, and air being unintentionally drawn from the attic into conditioned space for the various roof systems. These estimates indicate that all of the tested roof systems yield lower heat gains during the summer cooling season than the control roof with black shingles. The rank order is shown in Figure 7, with the percentage reduction of roof/attic related heat gain and the approximate overall building cooling energy savings. It appears that nighttime attic temperature and reverse ceiling heat flux have a significant impact on total daily heat gain, and with greater benefit to constructions that produce lower evening attic temperatures. Since the roof/attic ceiling heat flux, duct heat transfer, and duct leakage probably comprise about one-third of the total home cooling load, the above values can be modified to approximate the overall impact.

The rank order of the reductions is consistent with the whole-house roof testing that we completed for FPL in Fort Myers, which showed that white metal roofing brings about reductions on the order of 20% of space cooling. However, these results represent the first time that popular unfinished metal roofs have been comparatively evaluated.

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