# Cooling Related Performance of Finished and Unfinished Metal Roofing Systems

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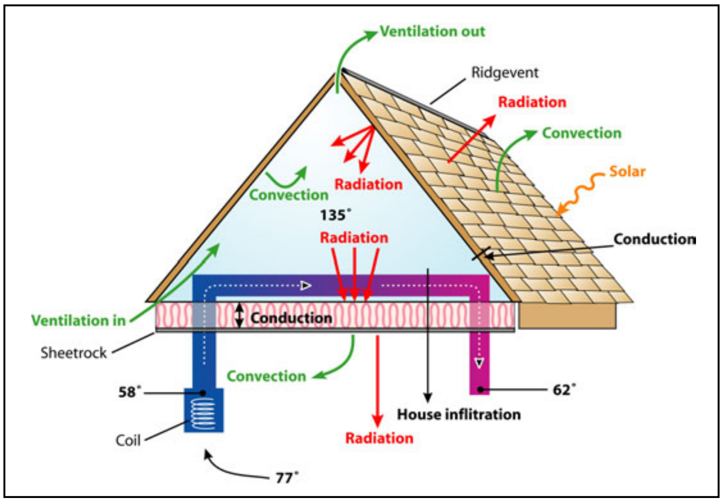
## ABSTRACT

This paper presents research conducted at Florida Solar Energy Center's Flexible Roofing Facility (FRF) in the summer of 2002. Testing evaluated how roofing systems impact residential cooling energy use with emphasis on finished and unfinished metal roofing types.

## Introduction

Improving attic thermal performance is fundamental to controlling residential cooling loads in hot climates. Research shows that the influence of attics on space cooling is not only due to the change in ceiling heat flux, but often due to the conditions within the attic itself and their influence on heat gain to duct systems and on air infiltration into the building. Figure 1 illustrates the fundamental thermal processes with a conventional vented attic.

**Figure 1. Vented Attic Thermal Processes**



The importance of ceiling heat flux has long been recognized, with insulation a proven means of controlling excessive gains. However, when ducts are present in the attic, the magnitude of heat gain to the thermal distribution system under peak conditions can be much greater than the ceiling heat flux (Parker et al., 1993; Hageman and Modera, 1996).[1] This is aggravated by the location of the air handler within the attic space – a common practice in much of the southern U.S. The air handler is poorly insulated but has the greatest temperature

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[1] A simple illustration - Assume a 2,000 ft$^2$ ceiling with R-30 attic insulation. Supply ducts typically comprise a combined area of ~25% of the floor area (see Gu et al. 1996), but are only insulated to between R-4 to R-6. With the peak attic temperature at 130$^{o}$F, and 78$^{o}$F maintained inside the house, a UA $\Delta T$ calculation shows a ceiling heat gain of 3,500 Btu/hr. With R-5 ducts in the attic and a 57$^{o}$F supply air temperature, the heat gain to the duct system is 7,300 Btu/hr – twice the ceiling flux.

difference at the evaporator of any location in the cooling system. It also has the greatest negative pressure just before the fan so that leakage into the unit is inevitable. As evidence monitoring of air conditioning energy use in 48 central Florida homes (Cummings, 1991) found that homes with the air handlers located in the attic used 30% more space cooling energy than those with air handlers located in garages or elsewhere.

Research also shows that duct supply air leakage can lead to negative pressures within the house interior when the air handler operates. The negative pressures can draw hot air from the attic down into the conditioned space through gaps around recessed light fixtures or other bypasses. The impact of duct heat gain and air leakage from the attic space shows that controlling attic air temperatures can be as important as reducing ceiling heat flux.

## Side-by-Side Roof Testing

During the summer of 2002, tests were performed on six different residential plywood-decked roofing systems with emphasis on increasingly popular metal roofing systems. The experiments were conducted at the flexible roof facility (FRF) located in Cocoa, Florida. The FRF is a 24 ft by 48 ft (7.3 x 14.6 m) frame building constructed with its long axis oriented east-west (Figure 2). The roof and attic are partitioned to allow simultaneous testing of multiple roof configurations. The orientation provides a northern and southern exposure for the roofing materials under evaluation. The attic is sectioned into six individual 6 foot (1.8 m) wide test cells spanning three 2 ft (0.6 m) trusses thermally separated by partition walls insulated to R-20 $ft^2$-hr-$^oF$/Btu (RSI-3.5 $m^2$-K/W) using 3 inches (7.6 cm) of isocyanurate insulation. The partitions between the individual cells are also well sealed to prevent air flow cross-contamination. The gable roof has a 5/12 pitch ($22.6^o$) and 3/4 inch (1.9 cm) plywood decking. On the attic floor, R-19 (RSI-3.3) unsurfaced batt insulation is installed between the trusses in all of the test bays (with the exception of Cell #2) in a consistent fashion. The attic is separated from the conditioned interior by 0.5 inch (1.3 cm) gypsum board. The interior of the FRF is a single open air conditioned space.

The facility allows reconfiguration with different roofing products and has been used to examine different levels of ventilation and installation configurations for tile roofing (Beal and Chandra, 1995). Testing has also compared reflective roofing, radiant barriers and sealed attic construction (Parker and Sherwin, 1998). Recent testing addressed the following questions:

- What is the performance of a standard black asphalt shingle roof with 1:300 ventilation?
- How does Galvalume® compare in thermal performance with a galvanized metal?
- How does a higher IR reflectance ivory metal shingle roof function relative to the lower reflectance one installed the previous summer? How does an innovative double roof construction compare with other types?
- How does a white standing seam metal roof perform relative to the unfinished metal?

## Test Configuration

**Cell #1**: Galvalume® 5-vee unfinished metal roof; 1:300 vented attic (1st year)
**Cell #2**: Black asphalt shingles with vented double roof deck with radiant barrier and 6" foam insulation on underside of bottom roof deck; unvented attic (2nd year)
**Cell #3**: IR reflective ivory metal shingles; 1:300 soffit and ridge ventilation (1st year)
**Cell #4**: Galvanized 5-vee unfinished metal roof; 1:300 ventilation (1st year)

**Cell #5**: Black asphalt shingles; 1:300 soffit and ridge ventilation (control cell; 15 years old)
**Cell #6**: White standing seam metal; 1:300 vented attic (7 years old)

All roofing materials were installed in a conventional manner according to manufacturer's specifications as shown in Figure 2.

**Figure 2. Flexible Roof Facility in Summer 2002 Configuration**

Samples of the new unexposed roofing materials were evaluated to establish their solar reflectance using ASTM Test Method E-903 (1996) and long wave emittance using ASTM E-408 (Table 1). Note the large difference in the infrared emissivity of the unfinished metal roofs. Galvalume® (0.28) is much lower than the other painted metals (0.83), but galvanized roofs are much lower still (0.04). Generally, low emissive surfaces reach higher temperatures since they do not readily give up collected heat back to the sky and its surroundings.

**Table 1. Tested Roofing Material Solar Reflectances and Emittances**

| Sample and Cell # | Solar Reflectance (%) | Long-wave emmittance |
|---|---|---|
| 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 |

Instrumentation for the project was extensive. Meteorological data were taken on air temperature, solar insolation, humidity and rainfall. All of the test cells were monitored from June – September of 2002. A number of temperature measurements using type-T thermocouples were made:

- Exterior surface of the roof and underlayment
- Decking underside
- Attic air at several heights within the attic
- Soffit inlet air and ridge vent exit air

- Insulation top surface
- Conditioned interior ceiling

## Test Results

### Attic Air Temperatures

The average summer day mid-attic air temperature profiles are shown in Figure 3. The profiles show the impact of the roofing options in reducing cooling energy use associated with attic duct heat gains and loads from unintended air leakage coming from the attic zone.

The statistics for the average, minimum and maximum mid-attic air temperatures over the entire summer (average day) are summarized in Table 2. These results show that the sealed attic with the double roof provides the lowest overall mean attic temperatures (77.7°F) and hence lowest attic duct system heat gains and impact from return air leakage from the attic zone. The next most productive roof combination in this regard is Cell #6 with the vented white metal roof (81.0°F). Very similar to this performance is Cell #3 with the IR reflective metal shingle roof (82.3°F). Next best in performance is Cell #1 with the Galvalume® metal roof and vented attic at 83.6°F. The lower emissivity galvanized metal roof (Cell #4) averaging 85.2°F, is least beneficial relative to the standard attic which averages 89.1°F.

**Figure 3. Measured Average Mid-Attic Air Temperatures Summer Period 2002**

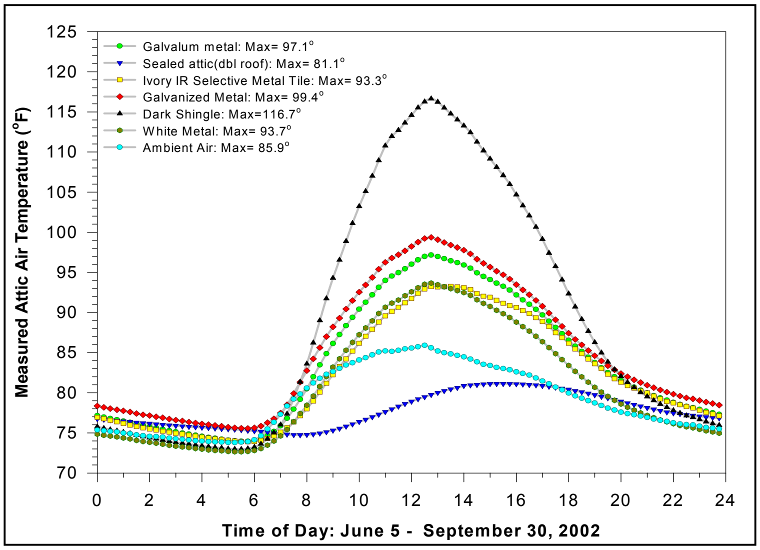


**Table 2. FRF: Measured Mid-Attic Air Temperatures (°F); June 5 - September 30, 2002**

| | Description | Mean | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|---|
| Outdoor Air | Ambient Air | 89.1 | 4.13 | 67.8 | 95.3 |
| Cell #1 | Galvalume® metal roof | 83.6 | 7.95 | 67.7 | 110.9 |
| Cell #2 | Double roof deck (sealed attic) | 77.7 | 2.16 | 72.9 | 84.8 |
| Cell #3 | High reflectance ivory metal shingle | 82.2 | 6.76 | 68.5 | 105.9 |
| Cell #4 | Galvanized metal roof | 85.1 | 8.16 | 68.3 | 113.7 |
| Cell #5 | Black shingle (control cell) | 89.1 | 15.39 | 67.0 | 139.6 |
| Cell #6 | White metal roof | 81.0 | 7.29 | 67.0 | 104.4 |

## Maximum Attic Air Temperatures

A comparison of the average daily maximum mid-attic air temperature for each cell against the average daily maximum ambient air temperature along with the corresponding temperature difference is shown in Table 3 below 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.

**Table 3. FRF Average Maximum Attic and Ambient Air Temperatures**

| Cell No. | Description | Average Max. Attic | Average Max. Ambient | Difference |
|---|---|---|---|---|
| Cell #1 | Galvalume® metal roof | 97.1°F | 85.9°F | + 11.2°F |
| Cell #2 | Double roof deck (sealed attic) | 81.1°F | 85.9°F | - 4.8°F |
| Cell #3 | High reflectance ivory metal shingle | 93.3°F | 85.9°F | + 7.4°F |
| Cell #4 | Galvanized metal roof | 99.4°F | 85.9°F | + 13.5°F |
| Cell #5 | Black shingle (control cell) | 116.7°F | 85.9°F | + 30.8°F |
| Cell #6 | White metal roof | 93.7°F | 85.9°F | + 7.8°F |

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 as the others do not have roof deck insulation, but instead have insulation on top of the ceiling. Comparing the 2002 summer results with 1999 and 2000 Cell #2 results (sealed attic without double roof and RB) however, shows that the double roof/RB combination average maximum mid-attic temperature difference from ambient was 4.7°F lower than the same sealed attic without the double roof. Its maximum mid-attic temperature of 81.1°F was also 7.1°F lower than the averaged 1999 and 2000 results.

The highly reflective ivory metal shingle (Cell #3) provided the coolest attic of the test cells without roof deck insulation. The average maximum mid-attic 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 (non-highly reflective) 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 highly reflective metal shingle on the same cell had an average maximum attic temperature 3.8°F higher than ambient.

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 against +7.8°F in the summer of 2002.

## Ceiling Heat Flux

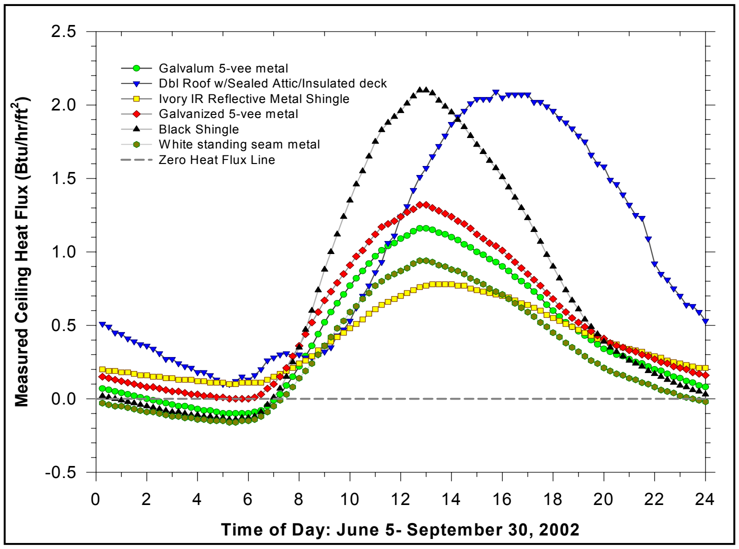
Table 4 and Figure 4 show ceiling heat fluxes over the 2002 summer. The uninsulated ceiling of the double roof with sealed attic (Cell #2) has a peak heat flux similar to that of the control (Cell #5), although with a significant time lag of over 3 hours. The mean heat flux for the double roof is 0.98 Btu/ft$^2$/hr, or 40% higher than the control. The double roof showed both the lowest mean and peak attic air temperature of the group, while the highest ceiling heat flux. This seemingly contradictory result stems from the fact that the attic floor (conditioned zone ceiling) of the sealed attic is not insulated so that the attic is unintentionally conditioned -- reducing the magnitude of attic temperatures by increasing heat transfer to the interior space.

The highly reflective ivory metal shingle roof (Cell #3) has the lowest peak ceiling heat flux at 1.19 Btu/ft$^2$/hr, and also has a relatively low mean flux of 0.39 Btu/ft$^2$/hr, which is slightly higher than the white metal roof at 0.30 Btu/ft$^2$/hr. 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$^2$/hr) performs similarly to the IR reflective roof. The galvanized metal had poorer performance (mean = 0.53 /Btu/ft$^2$/hr).

**Table 4. FRF Measured Ceiling Heat Fluxes (Btu/ft$^2$/hr); June 5 - September 30, 2002**

| Cell # | Description | Mean | Stddev | Min | Max | Flux Change Relative toCell #5 |
|---|---|---|---|---|---|---|
| Flux 1 | Galvalume® metal roof | 0.43 | 0.43 | -0.37 | 1.88 | -38.6% |
| Flux 2 | Double roof deck (sealed attic) | 0.98 | 0.71 | -1.11 | 3.33 | +40.0% |
| Flux 3 | High reflectance ivory metal shingle | 0.39 | 0.23 | -0.09 | 1.19 | -44.3% |
| Flux 4 | Galvanized metal roof | 0.53 | 0.45 | -0.32 | 2.09 | -24.3% |
| Flux 5 | Black shingle (control cell) | 0.70 | 0.78 | -0.38 | 3.32 | Ref |
| Flux 6 | White metal roof | 0.30 | 0.38 | -0.40 | 1.49 | -57.1% |

**Figure 4. Measured Average Ceiling Heat Flux Summer Period 2002**



## Estimation of Overall Impact of Roofing System

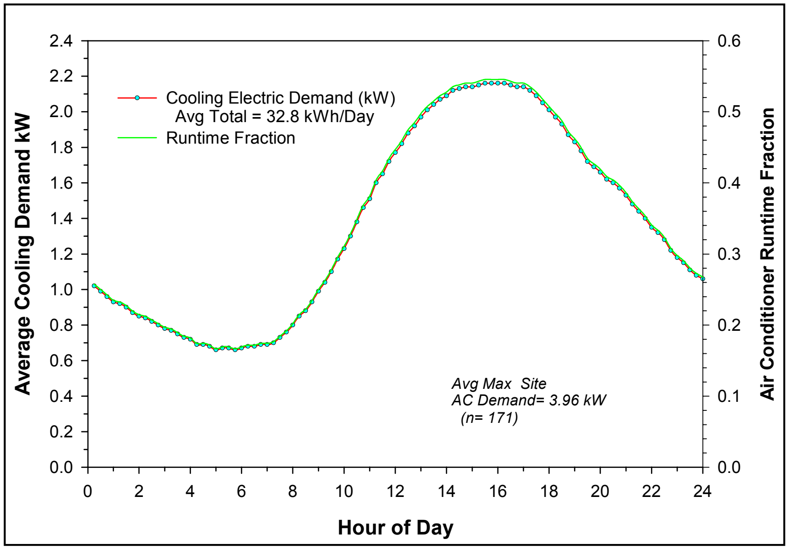
The impact of roofing on cooling energy is typically made up of three elements:

- Ceiling heat flux to the interior from the attic
- Heat gain to the duct system located in the attic space
- 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 impacts cooling energy use at all hours and affects 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 primarily occur only when the cooling system operates. Thus, the impact depends on the air conditioner runtime in a particular time interval. To obtain the average cooling system runtime, we used a large set of residential cooling energy use data. This data comes from 171 homes in Central Florida where the 15-minute AC power was measured for over a year (Parker, 2002).

For each site, the maximum demand during summer was also recorded to determine the maximum cooling system power. Thus, it is possible to determine the diversified runtime 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. Figure 5 shows the maximum average cooling system runtime is 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 this is an average summer day as determined by evaluating all data from June - September inclusive. It does not represent an extreme summer day condition.

**Figure 5. Average Air Conditioner Power and Average Runtime Fraction Over an Average Summer Day in a Large Sample of Central Florida Homes**



To estimate the impact of each roofing system, we assume a typical single-story home with 2,000 $ft^2$ of conditioned floor area. Three equations then estimate the impacts of duct heat gain ($Q_{duct}$), attic air leakage to conditioned space ($Q_{leak}$) and ceiling heat flux ($Q_{ceiling}$).

For duct gains, heat transfer is estimated to be:

$Q_{duct}$ = $(Area_{duct}/R_{duct}) * (T_{attic} - T_{duct,air}) * RTF$

Where:

$Q_{duct}$ = cooling load related to duct gains (Btu/hr)
$Area_{duct}$ = 25% of conditioned floor area or 500 $ft^2$ (Gu et al., 1996, see Appendix G)
$R_{duct}$ = R-6 flex duct
$T_{attic}$ = attic air temperature measured in FRF test cells
$T_{duct, air}$ = typical air temperature leaving evaporator ($58^oF$)
RTF = typical air conditioner runtime fraction (Figure 5)

Duct heat gain will favor the double roof sealed attic construction with lower attic temperatures. For attic air leakage to conditioned space, the estimated heat transfer is:

$Q_{leak}$ = $Flow * PctLeak * PctAttic * 1.08 * (T_{attic} - T_{interior}) * RTF$

Where:

$Q_{leak}$ = cooling load from air leakage to conditioned zone from attic (Btu/hr)
Flow = air handler flow; 4-ton system for 2000 ft$^2$ home, 400 cfm/ton = 1600 cfm
PctLeak = duct leakage assumed as 10% of air handler flow
1.08 = air specific heat density product per cfm (Btu/hr/cfm $^{o}$F)
PctAttic = 33% of duct leakage is assumed to be leakage from the attic (see Figure 1)
$T_{attic}$ = attic air temperature measured in FRF test cells
$T_{interior}$ = interior cooling temperature (75$^{o}$F)
RTF = typical air conditioner runtime fraction (Figure 5)

Heat flux is proportional to the house ceiling area and is estimated as:

$$Q_{ceiling} = Area_{ceiling} * Q_{flux}$$

Where:

$Area_{ceiling}$ = 2,000 ft$^2$
$Q_{flux}$ = measured ceiling heat flux from FRF data

So the total heat gain impact of a roofing systems is:

$$Q_{tot} = Q_{duct} + Q_{leak} + Q_{ceiling}$$

Figure 6 shows the combined roofing system heat gain estimated for 2,000 square foot houses with each of the six tested roofing systems. Figure 7 breaks down the $Q_{duct}$, $Q_{leak}$ and $Q_{ceiling}$ components of Figure 6 for the Cell #5 control roof to show the relative thermal contribution of each.

**Figure 6. Combined Impact of Duct Heat Gain, Air Leakage and Ceiling Heat Flux on Space Cooling Needs on an Average Summer Day in 2,000 ft$^2$ Home**

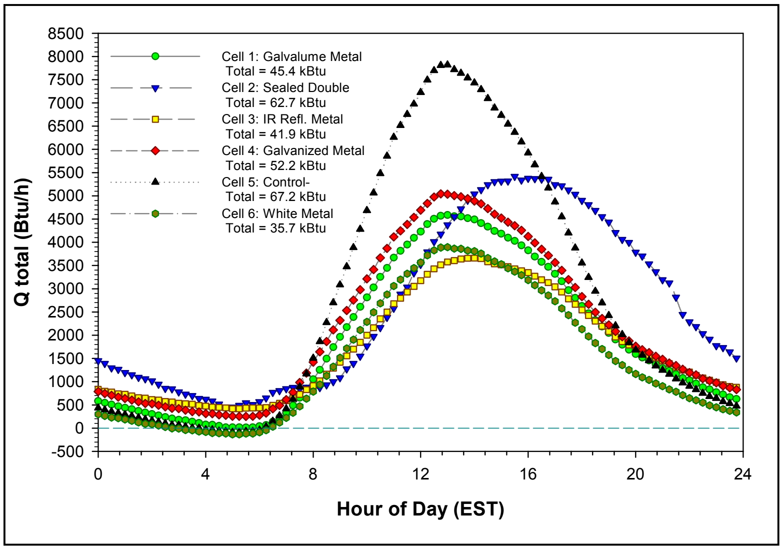


**Figure 7. Components of Estimates Daily Heat Gain Due to Duct Heat Gain, Air Leakage from the Attic to the Conditioned Space and Ceiling Heat Flux for Control Cell #5**

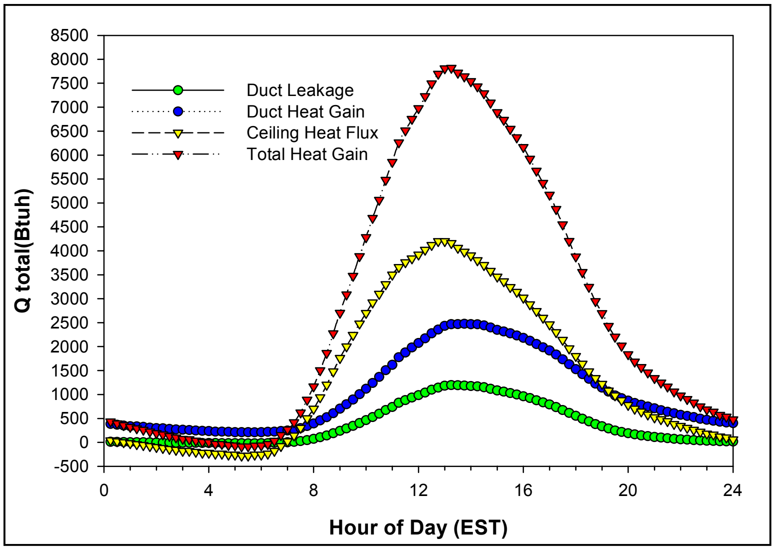


Table 5 shows the relative impact on space cooling and performance compared to the control.

**Table 5. Combined Ceiling Heat Flux, Duct Heat Gain And Attic Duct Leakage Impact in a 2000 sqft Home**

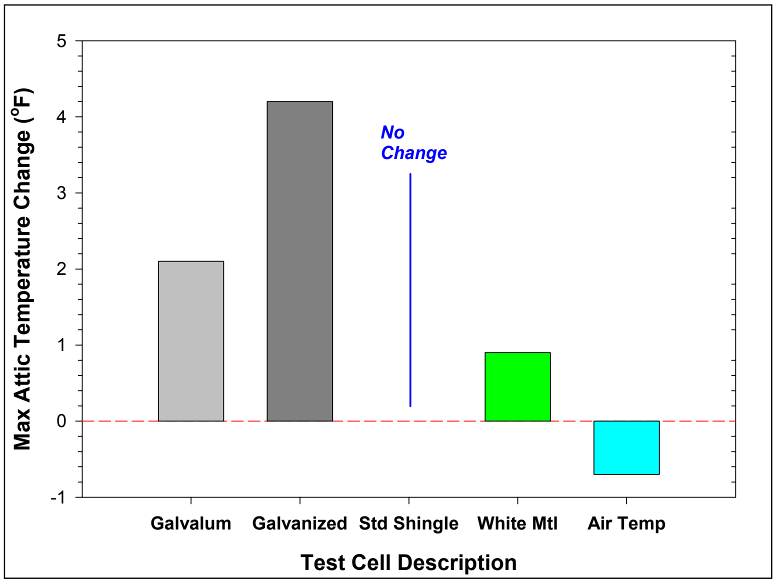
| Case | | Average Daily kBtu from Roof/Attic | Percent Heat Gain Difference Relative to Control |
|---|---|---|---|
| Cell #1 | Galvalume® metal roof | 45.4 | -32.4% |
| Cell #2 | Double roof deck (sealed attic) | 62.7 | - 6.7% |
| Cell #3 | High reflectance ivory metal shingle | 41.9 | -37.6% |
| Cell #4 | Galvanized metal roof | 52.2 | -22.3% |
| Cell #5 | Black shingle (control cell) | 67.2 | 0.0% |
| Cell #6 | White metal roof | 35.7 | -46.9% |

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 provides the lowest reduction. The 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 less adequately maintain their reflectance and emissivity properties over the long term as compared with the Galvalume® product due to the better corrosion resistant properties of the later's aluminum-zinc alloy. The preliminary data in Figure 8 verifies this expectation.

**Figure 8. Increase in Measured Average Maximum Mid Attic Air Temperature In 20003 compared with 2002**



This plot shows data on maximum average daily attic air temperature from the summer of 2003 compared with that of the summer of 1992 looking at three metal roofing types compared with the dark shingle: white standing seam, galvanized and Galvalume®. While the average maximum outdoor air temperature was 0.7°F cooler, we note that each product showed some signs of weathering and increased solar absorptance and resulting attic heating.

The standard dark shingle roof showed no change in its average maximum attic air temperature (116.7°F). However, note that the average maximum temperature in the attic under galvanized metal roof was 4.2°F hotter than the previous year. The Galvalume® roof average 2.1°F hotter 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 fits anecdotal observation (Tennessee Williams "Cat on a Hot Tin Roof."). After additional years of exposure, we expect the Galvalume® and galvanized would look more different in thermal performance. Galvalume® is expected to better maintain its performance with most weathering occurring within the first year. Within the project, performance is being monitored for a third year in the same configuration to examine any further changes due to weathering.

## Conclusions

Our test results from the summer of 2002 allowed comparison of the relative thermal performance of finished and unfinished metal roofing systems under typical Florida summer conditions. 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 with the sealed attic construction. Its attic temperatures were also much lower than the conventional dark shingled attic test 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 mid-attic 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 strategies tested (due to the uninsulated ceiling with this system), reducing its improvement over the standard dark shingle roof in the control home to a modest 7% reduction to 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 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 infrared emittance (0.40) which we expected to hurt its performance. The monitoring bore out this fact. 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 a 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.

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 constructions. These estimates indicate that all of the tested roof configurations yield lower heat gains during the summer cooling season than the control roof with dark shingles. The rank order is shown in Figure 9 with the percentage reduction of roof/attic related heat gain (and the approximate overall building cooling energy savings)[2]. Since the roof/attic ceiling heat flux, duct heat transfer and duct leakage likely comprise about a third of the total home cooling loads, the above values are modified to approximate the overall impact.

| | Roof-related Savings | Overall Savings |
|---|---|---|
| • White metal: | 47% | 15% |
| • High reflectance ivory metal shingle: | 38% | 12% |
| • Galvalume® unfinished metal roof : | 32% | 11% |
| • Galvanized unfinished metal roof: | 22% | 7% |
| • Double roof with sealed attic | 7% | 2% |

The rank order of the reductions are consistent with the whole-house roof testing completed for FPL in Ft. Myers (Parker et al., 2001) which showed white metal roofing as having 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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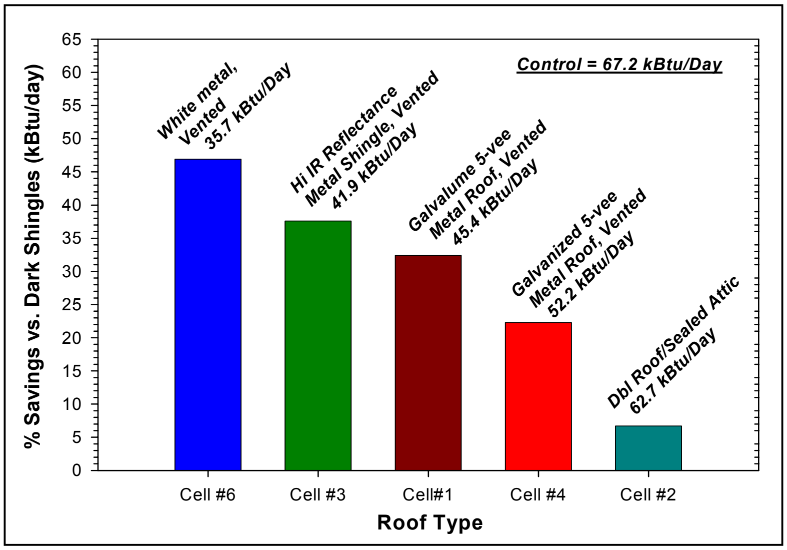
[2] One emerging fact is that nighttime attic temperature and reverse ceiling heat flux have a significant impact on the total daily heat gain, and with greater benefit to constructions that produce lower evening attic temperatures.

**Figure 9. Percentage Savings in Daily Total Roof/Attic Related Heat Gain**



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