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Energy Savings From Industrialized Housing Construction Systems And Roofing Tiles

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ABSTRACT

Side-by-side tests were conducted in Cape Canaveral, FL to compare the cooling and heating energy use and electric peak demand requirements for two industrialized (Dow and Dome) and one conventional room-sized prototypes. The industrialized prototypes saved 11% to 16% in cooling energy and 45% to 56% in heating energy. The industrialized prototypes peak demand savings was 16% to 23% for cooling and 39% to 42% for heating. The energy performance of the Dome prototype was slightly better than that of the Dow. These results were as expected and are largely due to the higher insulation levels and greater air tightness of the industrialized prototypes.

Data are also presented on summertime shingle temperatures on dark roofs over vented attics and over volume ceilings with no attic spaces. It was found that shingle temperatures over vented roofs ran 10 to 15 °F cooler during peak summer conditions.

In search of a more energy efficient roofing material to cover roofs without attics, tests were conducted on roofing tiles. Side-by-side tests on several scale model roofs were conducted to determine the most cost-effective roof tile configuration. This was then retrofitted on to the Dow prototype. As a result, its cooling performance improved measurably and became similar to that of the Dome prototype.

INTRODUCTION

This paper presents results of testing carried out from August 1990 through June 1991 (FY90 and FY91) as part of the Energy-Efficient Industrialized Housing project. The purpose of this project is to develop industrialized housing concepts that are energy efficient, affordable and of high quality. One of the tasks of this project is to test construction methods and materials. In this task, side-by-side field-testing of industrialized and conventional house prototypes was accomplished. This testing benefits the industrialized housing industry by providing information on the performance of its product, which allows it to revise the design and construction processes and improve the house quality and marketing. The energy efficiency of industrialized houses has not been compared to conventional houses before. However, different types of walls in conventional houses have been compared, (Burch, Krintz and Spain 1984; Burch, Malcolm and Davis, 1984). There, the authors compared six house prototypes with different wall structures. The walls tested were insulated lightweight wood frame, uninsulated lightweight wood frame, insulated masonry with outside mass, uninsulated masonry, log, and insulated masonry with inside mass.

Recent research data from Florida, the Northwest and other regions of the country show that high-R-value components and highly efficient mechanical systems are necessary but not always sufficient to achieve energy efficiency. In many homes with such “energy-efficient” products, significant energy waste is caused by leaky duct systems, poorly applied insulation, convective air gaps and similar component installation problems (Cummings, 1990; Parker, 1989). Such defects can also lead to air quality and moisture problems that result in expensive repair costs for both builders and homeowner. Industrialized home construction, a process that employs suitable quality control methods can identify and rectify such energy- related problems in the construction process and ensure a higher quality, more energy- efficient and more affordable home.

PROTOTYPE HOUSES AND TESTING PROTOCOLS

Three one-room test buildings, two industrialized houses and one conventional, were constructed and tested at Florida Solar Energy Center (FSEC) at Cape Canaveral, Florida during 1990 and 1991.

The conventional prototype (Base) is of standard 2x4 construction. It embraces a 16 ft x 12 ft space with an 8-ft-high ceiling. The wails and attic are insulated to R-11 and R-19, respectively. The attic is vented with full-length ridge and soffit vents. The Base prototype, which was constructed by FSEC personnel, appears on the right foreground in Figure 1: a photograph of the three prototypes.

Figure 1. Industrialized and Conventional Prototypes

The other two prototypes, also shown in Figure 1, are made from panels constructed in a factory and erected at the site. Panels for the rectangular prototype (DOW) was made from extruded polystyrene (styrofoam), manufactured by the DOW Chemical Company, sandwiched between two oriented strandboards. The styrofoam is 4" thick for wall panels and 6" thick for roof panels. DOW Chemical Company supplied the panels, which were manufactured by a panelizer in the Midwest. FSEC personnel erected this structure.
The third prototype (DOME) is also made out of factory-constructed panels, which are made from 7" of expanded polystyrene sandwiched between gypsum wall board and a lightweight, concrete outer shell. The manufacturer, American Ingenuity, made a partial donation of the panels and erected the dome.

To reduce construction costs and insure consistency of test results, all three prototypes have only one window which is located in the north entry door and no roof overhangs. Each prototype is equipped with a 5200 Btu/hr, EER=9.0, window air conditioner and a 1.5 KW electric heater. All prototypes have negligible ground coupling as their floor slabs sit on 2" of rigid insulation over another 4" thick concrete slab. Table 1 compares the physical characteristics of the three prototypes.

Table 1
Prototype Characteristics

	Base	Dow	Dome
Floor area, sq ft	192	192	251
Interior volume, cu ft	1370	1710	2000
Wall insulation	R-11	R-20	R-28
Roof insulation	R-19	R-30	R-2
Attic	Vented	None	None
Roof color	Dark	Dark	Medium
Roof solar absorptance	0.91	0.91	0.58
Air infiltration rate (ach) at 50 Pa pressure	3.9	2.4	1.7
Air infiltration rate1 (air changes/hr)	0.20	0.12	0.09
Calculated thermal transmittance, UA (Btu/hr/°F)	58.4	39.9	37.8

Effective overall thermal transmittance, Uo (Btu/hr/sq.ft. of floor area/°F)	0.30	0.21	0.15
Effective overall thermal transmittance, Uo (Btu/sq.ft. of floor area/°F-day)	7.3	5.0	3.6

1 Air infiltration estimated from blower door results as ACH50/20.

The tests consisted of four parts: a) cooling test in 1990, b) heating tests in January-March 1991, c) roofing tile tests, and d) cooling tests in 1991. The cooling test of summer 1990 were conducted by air conditioning the rooms to a set point of about 77°F. The air conditioners were controlled by electronic thermostats, and run in the positive ventilation mode so that they took in some outside fresh air. This mode ensured that the rooms simulated occupancy and maintained reasonable humidity levels (45%-55% RH). To simulate other internal loads, two light bulbs were kept on at all times, imposing a constant load of 93 Watts. The heating test was done in winter 1991 by heating the rooms to a set point of 72°F. The heaters were controlled by the same electronic thermostats.

Figure 15.
Janet McIlvaine tests building tightness

In early 1991, experiments on small-scale roofs were begun to investigate the performance of roofing tiles and other roof coverings. The motivation was to enhance the summer performance of the Dow prototype by replacing the dark shingle roof with a more energy efficient as well as aesthetic roof cover. Figure 10 shows the small roof models in front of the room sized prototypes. Each has a plan area of 24 sq ft (4 ft x 6 ft) and a roof pitch of 6:12 representative of residential roof pitches. The roof models face north and south and are located above ground on concrete blocks as shown in Figure la. Each is made of three trusses two ft on center. The attic space is unvented and has R-5 at the ceiling plane. The gable ends are insulated to R-10 to minimize heat gain. The roof decking is made of plywood and all roofs have roll roofing for waterproofing. The instrumentation consist of a single thermocouple sandwiched between the decking and the roll roofing on the south facing roof. Several roof cover materials were tested. Several configurations of concrete tiles, a clay tile, two colors of shingles, and others.

Figure 10. Small scale roof models to test roof coverings

On the basis of these tests, the conventional concrete tile was deemed to be the most effective solution. The dark shingles were then removed and red concrete tiles installed on the Dow prototype (see Figure 11). Cooling tests were run again in 1991 to determine the performance of the improved Dow prototype.

Figure 11. The Dow prototype after retrofit with red concrete tiles.

The following data were recorded for each of the prototypes:

- Room temperature
- Room humidity
- Air-conditioner supply and return air temperatures
- Air-conditioner run time
- South and north roof shingle temperatures for Base and Dow
- Air-conditioner energy consumption
- Internal load Wattage.

In addition, an external weather station recorded ambient air temperature, humidity, wind speed, wind direction and horizontal total solar radiation.

All temperatures were measured with type T (copper-Constantan) thermocouples accurate to 0.3°F as determined by calibration to standard thermometers. The Watt transducers have an accuracy of 0.2%. The data channels were scanned every 15 seconds and averaged every 15 minutes. The data were then, stored and analyzed on a minicomputer. In addition, humidity levels, air-conditioner Wattage and internal-load Wattage were recorded manually twice daily for calibration purposes. See Chandra et al. (1991) for details on construction and instrumentation.

Figure 16.
Power recording meters

Figure 17. Engineer Elvis Gumbs
adjusts thermocouple arrays

RESULTS

Cooling Experiment During 1990

Considerable effort was spent devising test procedures, ensuring identical mechanical system performance and calibrating instrumentation. Good data are available for two test periods encompassing about 16 days in August 1990. Figure 2 shows the ambient and prototype temperatures for these two test periods.

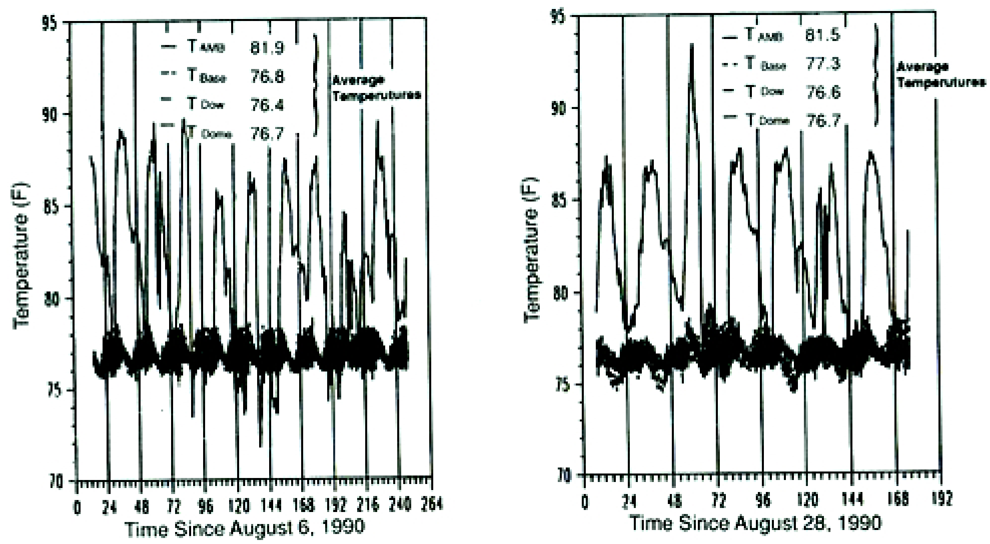

Figure 2. Ambient and Indoor Temperatures

The internal temperatures of three prototypes overlap each other and create the blur on Figure 2. Even though the average internal temperatures (indicated on top of the graph) match closely, there is considerable diurnal variation. Consequently, it is not possible simply to compare raw power consumption data to estimate comparative performance of the prototypes.

Figure 3 shows the manually recorded relative humidities inside the prototypes for the same periods. They vary between 45% and 55% RH and, on the average are close to each other.

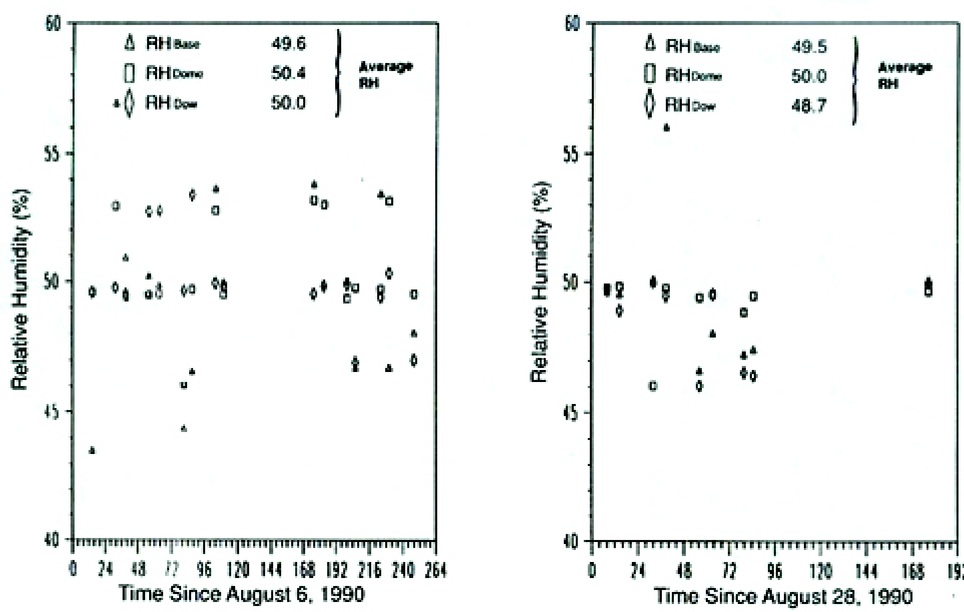

Figure 3. Relative Humidity

Figure 4a, 4b and 4c correlate the daily air-conditioner energy use to the daily average temperature difference between the ambient and interiors for the Base, Dome and Dow respectively. Daily averaging produced better correlations than averaging for shorter periods of time. The correlation was improved (i.e., lower standard deviation) by adding the daily total horizontal solar radiation value (given as SR in the correlation equation listed at the top of the graph). The significance of the solar radiation effect on the daily cooling load was also proved by the T. statistics test.

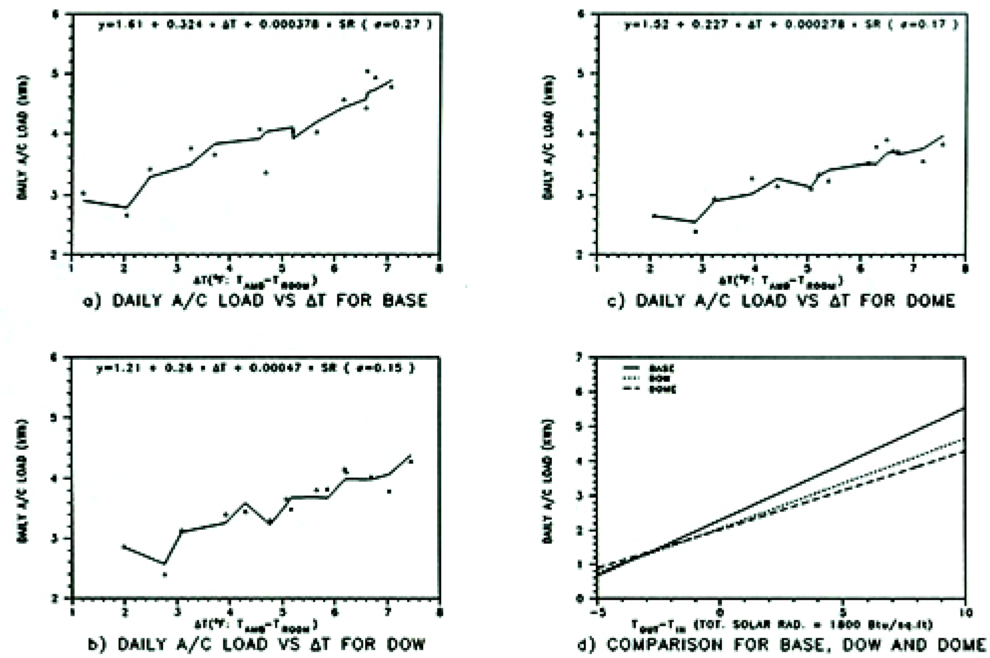

Figure 4. Air Conditioner KWh Use Of Industrial (Dow, Dome) And Conventional (Base) Prototypes

The comparative performance of the three prototypes on an average sunny day (SR= 1800 Btu/sq ft. day) is shown in Figure 4d. The figure shows that both industrialized constructions perform better than the Base.

To provide a single comparative measure for the construction types, the following analysis was performed for several southeastern cities where the summer conditions are similar to the test conditions. The hourly data from the typical meteorological year for the cooling season were averaged into daily average temperature and daily total solar radiation values. The cooling season was defined to be those months for which the average temperature exceeded 72°F. The daily average data were then applied to the correlation equations for the three prototypes. Summation of the daily load was done except when the load was negative. The seasonal savings from Dow and Dome over Base were then calculated. The results of the analysis are shown in Table 2.

Table 2
Cooling Energy Saving Percentages Relative to Base

City	Cooling Months	Dow	Dome
Miami, FL	Apr-Nov	12.2	13.4
Orlando, FL	May-Oct	11.7	13.6
Jacksonville, FL	May-Sep	11.0	12.8
Houston, TX	May-Sep	12.7	15.9

The results of Table 2 indicate a savings of 11% to 16%. While not dramatic, the results are as expected. Figure 5 shows only 22% of the cooling load for a typical house is due to the heat gain through the roof and the walls (Fairey, 1986).

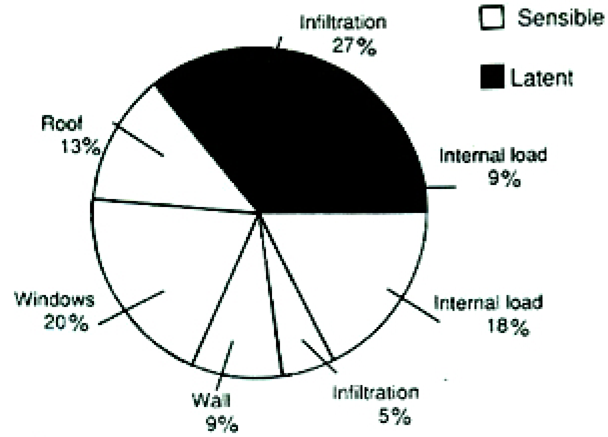

Figure 5. July Cooling Load Sources for a 1500 sq ft Base House in Orlando, FL

This analysis is meaningful only if real houses perform similarly to the prototypes. The authors believe that is indeed the case for the following reasons:

- The average daily air conditioning energy consumption for the Base prototype is 0.020 kWh/sq ft. day. This is very close to that measured for 100 homes in Miami for the month of August. The measured value for those 100 homes was 0.022 kWh/sq ft. day (FPL, 1980). The FSEC test site is in a costal area where the summer climate is close to that of Miami.
- The sensible internal load from the 93-watt light bulbs is 2.23 kWh/day. Since the air-conditioner EER is about 9.0 (i.e., a COP2.6), the air-conditioner electricity consumption to remove this load is about 0.84 kWh/day or 0.0044 kWh/sq ft. day. This is 20% of the measured cooling energy use. This 20% is quite close to the 18% contribution of sensible internal loads to the cooling loads in a full-scale house as seen in Figure 5.

The preceding comments pertain to the Base prototype. Some additional comments on the Dome construction system follow:

- The Dome prototype has a floor area of 251 sq ft, which is 31% greater than the Base. As a result, on a per-square-foot basis, the savings from the Dome will be greater than those indicated in Table 2. In other words, the cooling energy savings from the Dome will be between 33% and 36% compared to the Base. This, of course, assumes that each square foot of the dome is as functionally valuable as a rectangular floor plan. Also note that part of the savings results from the lighter color of the Dome.
- The Dome prototype has smaller-sized panels than full-sized domes. As a result, the ratio of the seam area to surface area of the prototype is greater than in a full-scale dome. Since the seam area has a lower R-value, the prototype thermal integrity is somewhat poorer than a full-scale dome.
- Full-scale domes always have duct systems in the conditioned space. FSEC tests (Cummings, 1990) have shown that ducts in attics increase air- conditioning energy use by 25% on the average. Thus, full-scale domes can be 25% more energy efficient. However, it is quite possible to design ducts in conditioned spaces in the Dow and Base construction systems.

Another aspect of the work that is of interest to the utility companies is the effect on peak electrical demand imposed by residential air conditioners. Figure 6a-6c plot the average hourly electrical demand of the three prototypes as a function of the hourly ambient-to-indoor temperature difference. For small temperature differences the data are scattered and do not seem to follow any trend; however as the temperature difference goes higher than 50F the data seem to take a linear trend. As a result, a linear fit was made for temperature differences higher than 5°F. The temperature difference was computed with lag; i.e., the ambient temperature was measured a certain time before the room temperature was. The lag time was chosen to minimize the data scatter. The linear fit was done for all lag intervals in increments of 15 minutes to find the minimum value of the standard deviation. The lag time was found for the Dow and Dome prototypes to be 2 hours and 1.5 hours respectively, while the lag time for the Base was only one hour. This indicates that the Dow and Dome prototypes not only reduce the peak demand but also shift the demand to a time that is more beneficial to the electric utility companies.

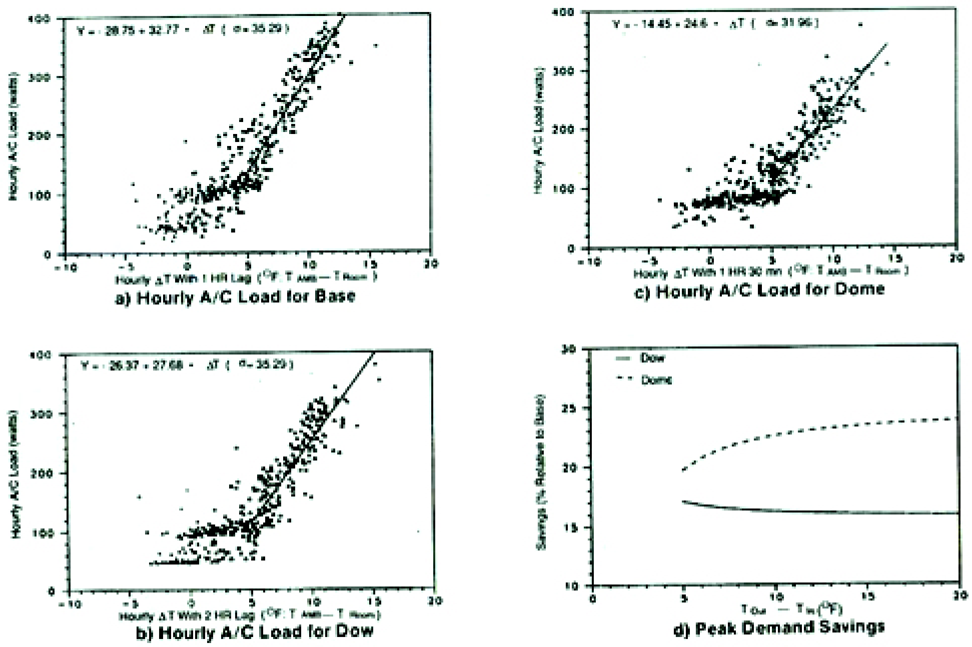

Figure 6. Hourly (and Peak) Air Conditioner (A/C) Electricity Consumption of Industrial (Dow, Dome) and Conventional (Base) Prototype

Figure 6d compares the savings of peak demand for the Dow and Dome prototypes compared to the Base. The savings are fairly constant and higher than the average savings.

The roof of both the Base and Dow prototypes are covered with dark-colored shingles. However, the Base has a vented attic above an 8-ft ceiling, while the Dow prototype has no attic space above its vaulted ceiling. To determine the effect of attic venting, the shingle temperatures were measured and compared between the two construction types. Figure 7a presents the temperatures measured under a shingle tab on the south roofs of both prototypes. The figure shows that, under peak solar conditions, the Dow shingles were 170°F, or about 15°F hotter than shingles on the Base prototype. The shingle temperatures on the north roof showed a similar pattern, with the maximum Dow shingle temperature reaching 150°F, which was 10°F hotter than those on the Base (Figure 7b). The authors do not know whether these small increases in shingle temperature are detrimental to shingle durability.

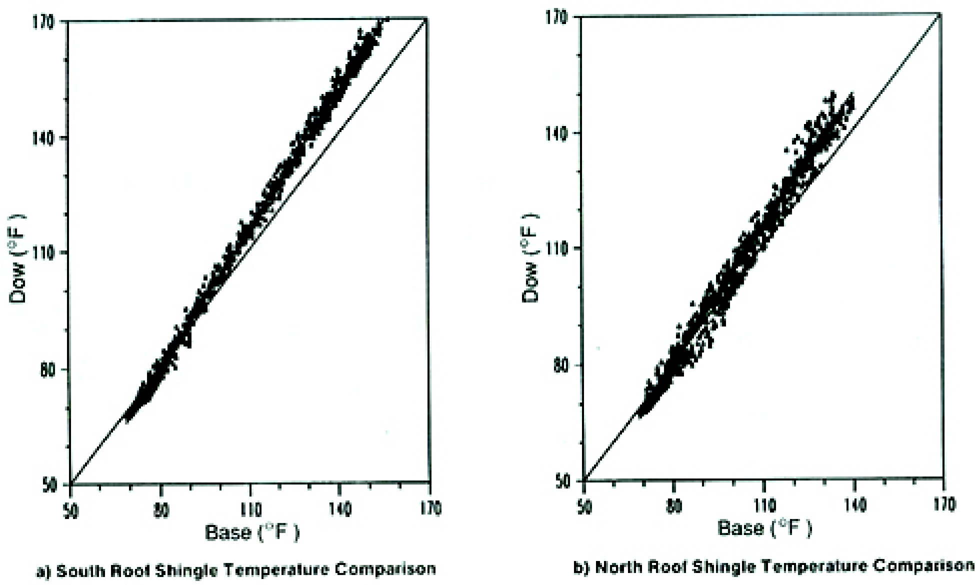

Figure 7. Shingle Temperatures

Heating Experiments

The heating experiments were analyzed the same way as the cooling experiments. However, because the weather in central Florida does not get cold for long periods of time, heating data were limited. A total of 12 days of data were collected: 3 days in January, 5 days in February and 4 days in March. These days were the only days where heating was required in all three houses to keep their indoor temperatures at 72°F. The average outdoor temperature during the test period was 56.6°F, while the average daily high temperature was 65.5°F and the average daily low temperature was 47.7°F.

As in the cooling experiment, daily averaging generated the best correlations. However, since most of the heating was done at night the solar radiation was not a big factor, and was excluded from the correlation. The insignificance of the solar radiation was also proved by the T statistics test. The heating energy consumption was related to the daily average temperature difference between ambient and indoor and is shown in Figure 8 a, b and c for the Base, Dome and Dow respectively. The constant -2.4 kWh was forced on the correlation because of the internal load (total daily internal load = 2.4 kWh). Because the weather did not allow a longer continuous test period, thermal capacity was a factor and caused the data scatter. In addition, the weather was not cold enough during the day time to keep the heater on for all hours. This enhances the effect of thermal capacitance.

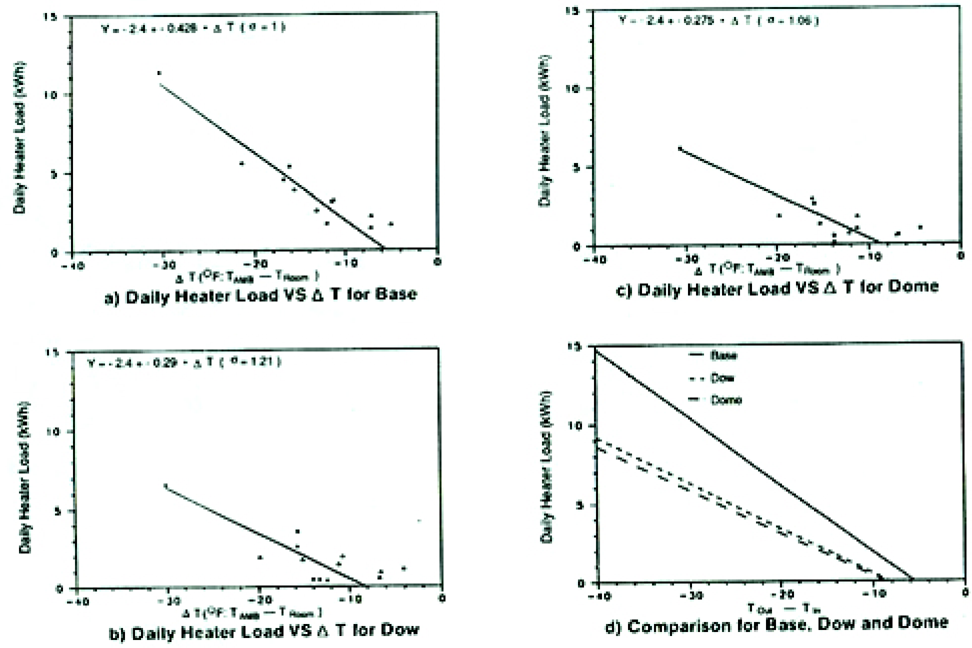

Figure 8. Daily Heat Requirements of Industrial (Dow, Dome) and Conventional (Base) Prototypes

Daily average temperatures from the weather tapes of certain southeastern cities were applied to the correlations, as in the cooling experiment. The heating season was considered as the months when the average temperature was lower than 65°F. The saving percentages were calculated and shown in Table 3. Unlike the savings in cooling energy, the savings in heating energy are quite high. Again, this is expected as internal loads and solar gains reduce heating energy and increase cooling energy consumptions.

Table 3
Heating Energy Saving Percentages relative to Base

City	Heating Months	Dow	Dome
Orlando, FL	Dec-Feb	50.3	55.7
Jacksonville, FL	Nov-Mar	45.5	50.5
Houston, TX	Nov-Mar	45.2	50.1

Figure 9 a, b and c shows the hourly average heating energy consumption vs. the hourly difference between indoor and outdoor temperatures for the Base, Dome and Dow. A linear fit was made to find a correlation between the energy consumption and the difference in temperature. The hours when there was no heating were ignored. This correlation allows us to predict the peak demand. Figure 9d shows the savings in peak demand of the Dow and the Dome relative to the Base. The savings are around 40% for the Dow and 42% for the Dome for cold temperatures but as the temperature gets close to the room temperature the energy consumption for Base gets low and so do the savings from the Dow and Dome.

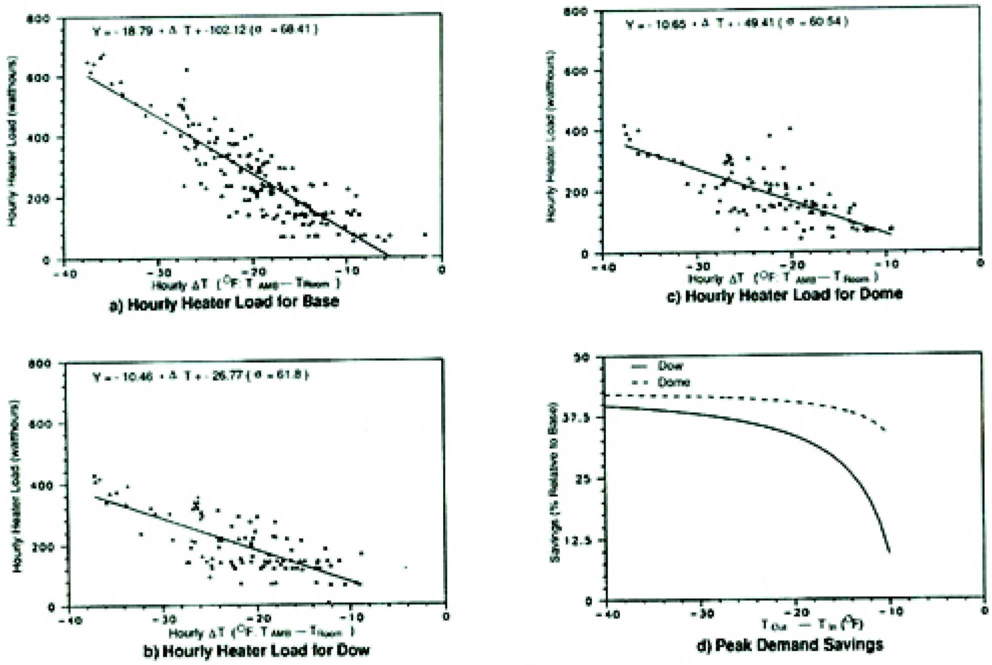

Figure 9. Hourly (and Peak) Heater Electricity Consumption of Industrial (Dow, Dome) and Conventional (Base) Prototype

Thermal transmittance of each prototype was calculated according to the ASHRAE Handbook of Fundamentals. The thermal transmittance times the area was found to be 17.1, 11.7 and 11.1 W/°F for the Base, Dow and Dome respectively. These values agree reasonably with the values found from the regression equations in Figure 9.

<u>Roofing Tile Tests</u>

Tests were begun in January 1991. First, null tests were run on five identical models all with roll roofing. The results for the roof deck temperatures are presented in Figure 12 for a warm January day.

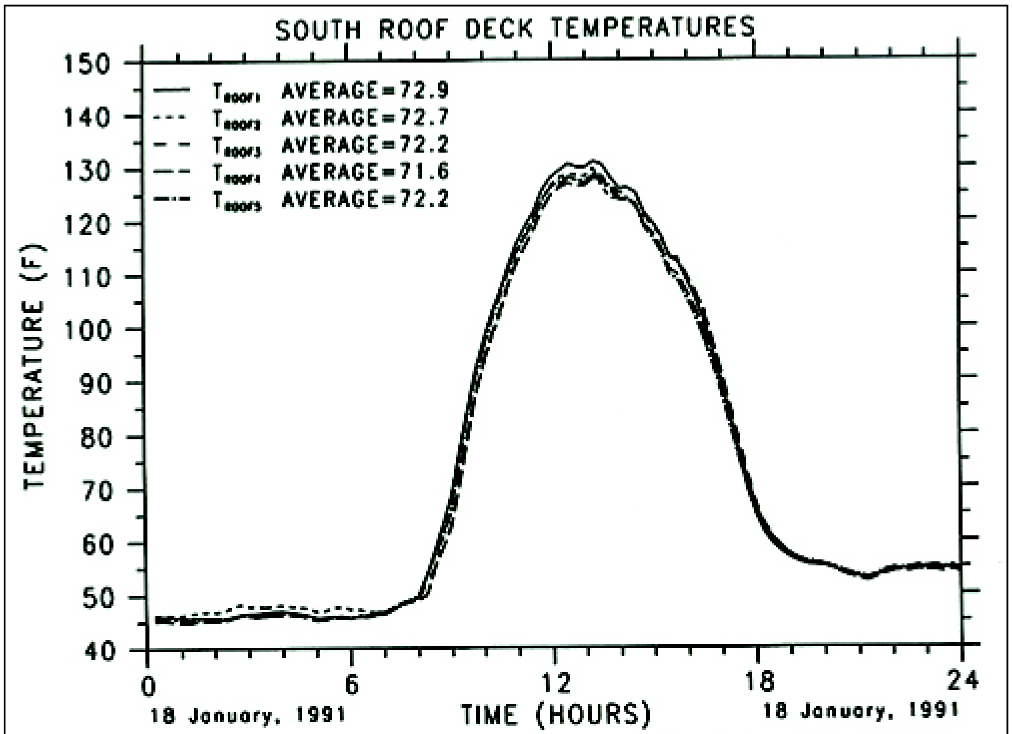

FIGURE 12 NULL TESTS WITH ROLL ROOFING ON ALL ROOFS

Although, the thermocouple accuracy is about 0.3°F, slight differences in construction result in a measurement uncertainty of about 2°F. At the conclusion of the null tests, the coolest roof was roofed with dark grey shingles, the same color as the basecase prototype, and a sixth identical roof prototype was constructed.

Results are reported for the first series of tests. In the first series of tests, the six roofs were:

- Grey Shingle, to match the color of the basecase roof
- White Shingle
- Red Concrete Tile on single battens, no radiant barrier (labelled tile,sb,nrb in Figure 13)
- Red Concrete Tile on single battens, with a radiant barrier (labelled tile,sb,rb in Figure 13)
- Red Concrete Tile on double battens, no radiant barrier (labelled tile,db,nrb in Figure 13)
- Red Clay Tile no battens, with radiant barrier (labelled tile,rb in plot).

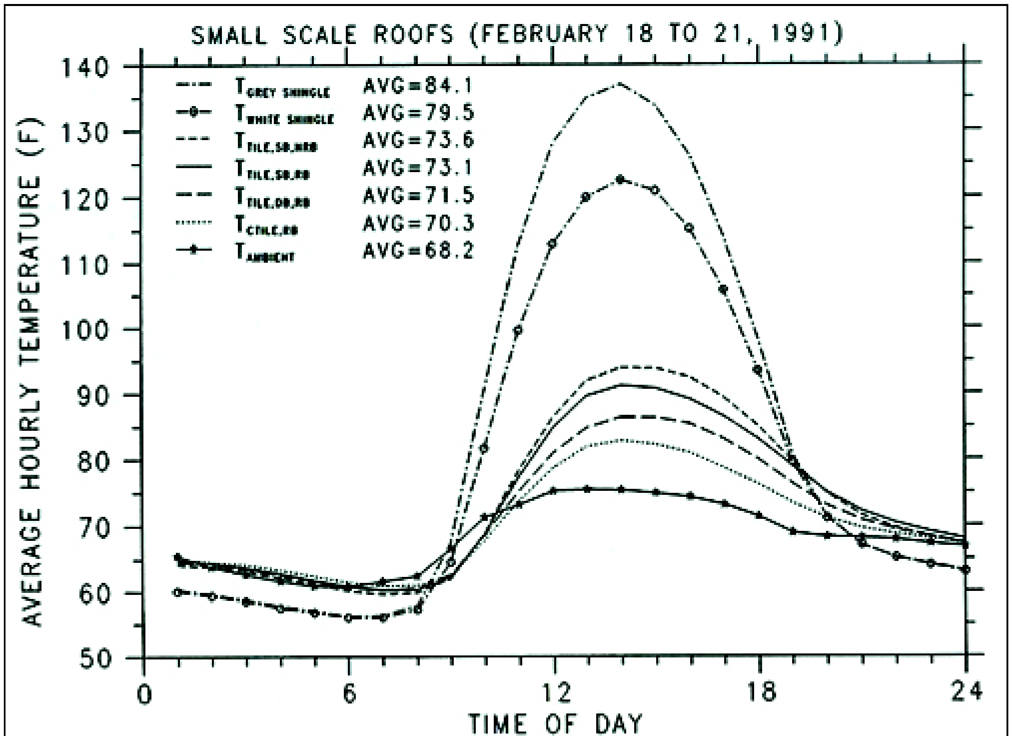

FIGURE 13 SOUTH DECK TEMPERATURES

The white shingles were the whitest that could be bought (they actually look light grey). Single batten refers to conventional installation of concrete tiles where they are nailed to ¾″ x 1.5″ (nominal 1″ x 2″) wood battens nailed to the roof decking. Double batten refers to two rows of battens. The bottom rows run up and down to the ridge and the top row runs horizontally like the single battens. The double batten geometry ventilates the space under the tiles better than the single battens. Radiant barrier refers to roofs where a low emittance reinforced aluminum foil material was glued to the underside of the tiles. All tile roofs were open (i.e., vented) rather than blocked off at the eave level.

Figure 13 presents results (i.e., average hourly south facing roof deck temperatures) for this first series of tests for four warm February days. Note that the white shingle roof is only marginally cooler than the black shingles. The performance of all tile roofs is much better than the shingled roofs. As expected better ventilated tile roofs perform better (compare the two curves labelled tile,sb,rb and tile,db,rb). The radiant barrier also improves performance (compare tile,sb,arb with tile,sb,rb). The clay tile roof (see Figure 1c) performed the best with the deck temperature never more than 8°F warmer than ambient. This is probably due to the barrel geometry which results in all tiles being ventilated rather than the clay material or the presence of the radiant barrier.

The data on Figure 13 clearly demonstrate the excellent performance of tile roofing in reducing summer time cooling loads. Double battens and radiant barriers performed better than the conventional single batten installation. Preliminary calculations indicated that the performance enhancements from double battens and radiant barriers will not be worth the cost. As a result the Dow prototype was retrofitted with red concrete tiles in a single batten configuration.

Cooling Experiments During 1991

Data were collected during May and June of 1991 following the 1990 protocols. Results from 34 days of data are shown in Figure 14.

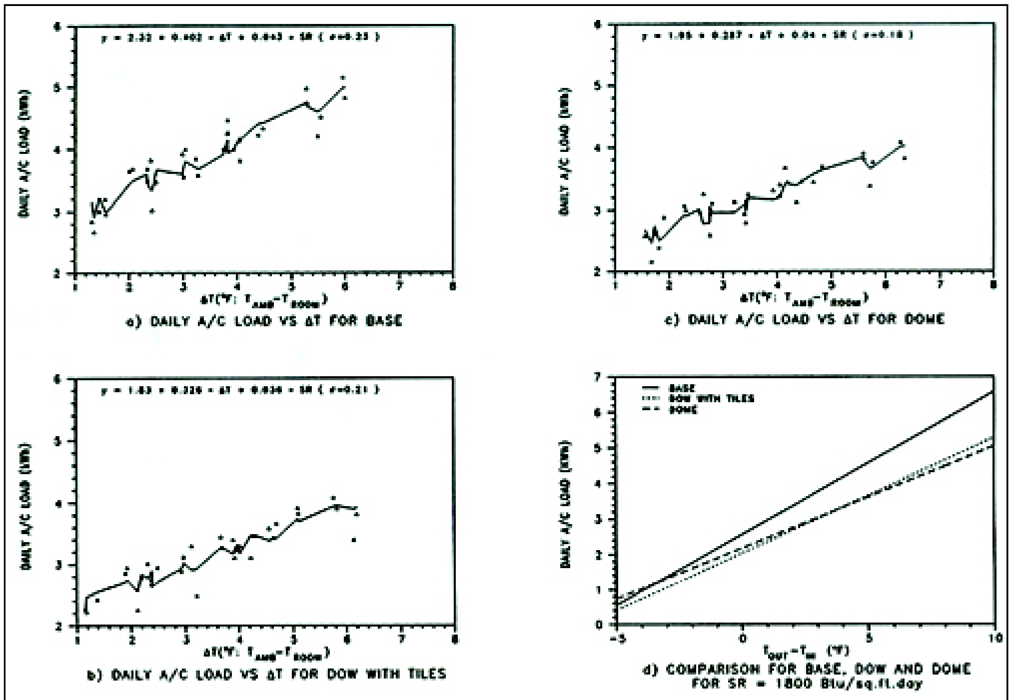

Figure 14. Air Conditioner KWh Use Of Industrial (Dow With Tiles, Dome) And Conventional (Base) Prototypes

Figure 14a through 14d are plotted in the same format as Figure 4a through 4d which described the 1990 experiments. The “bottom-line” may be found by comparing the two figures. If one overlays the two figures one sees that both the basecase and the Dome used more cooling energy in 1991 than in 1990 (Figure 4a, 14a and 4c,14c). As nothing was changed in the base or Dome, this indicates that the weather was hotter during the 1991 test period. However there is very little difference between the Dow with tiles in 1991 and the DOW without tiles in 1990 (compare figure 4b with 14b). Thus one concludes that tiles did indeed improve the cooling performance. This is also seen in figure 14d, where the cooling load for Dow with tiles is very close to that of the Dome prototype. As seen from Figure 4d, the Dow performance with dark shingles was somewhat poorer than the Dome.

CONCLUSION

Side-by-side field tests and analysis demonstrated the superior energy efficiency of two industrialized housing prototypes when compared to conventional construction. The superior energy performance is a result of the higher insulation levels and greater airtightness of the industrialized prototypes. Of course, conventional construction can also be made to better standards and equal or better performance can be achieved.

The purpose of these tests was not to determine a “winner”, but simply to establish the baseline performance level of available technologies today. The performance data have been valuable to the industry. Dow Chemical and AFM corporation have found the shingle temperature data to be useful. American Ingenuity used the test data for marketing purposes in Israel.

The excellent performance of concrete tile roofing in ameliorating summer cooling loads is encouraging. It may prove to be a cost-effective and aesthetic solution if its increased first cost can be amortized over its longer life time.

ACKNOWLEDGEMENT

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