Enhancement of Thermal Performance of Domestic Roofing System for Tropical Climes

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ABSTRACT

In the tropics in general and in the Caribbean in particular, domestic low-cost housing consists primarily of single-story structures. In these houses the roof typically consists of corrugated galvanized sheet metal with or without a ceiling. The roof, because of its orientation (typically < 20°) to the high-altitude tropical sun, has been identified as the building element that receives the greatest portion of the direct incident solar radiation. However, its generally poor thermal design leads to heat stress conditions in the occupied space. There is, therefore, an urgent need to provide low-cost strategies for thermal performance enhancement to alleviate this heat stress problem.

The overriding concern in a heated roof is the downward heat intrusion, which occurs primarily via radiation from the heated underside of the cladding. With this in mind, a series of side-by-side tests using model roof assemblies have been conducted to determine the potential of radiant barriers for enhancing the thermal microclimate of local domestic housing.

Because of the transient nature of weather, a means of correlating the results of different tests was required. Direct comparison of all the possible test configurations was not economically feasible. A comparative system was therefore adopted, using two identical test models, one an unchanging reference and the other a test unit for examining the behavior of various radiant barrier and ceiling configurations. Results of the initial null testing showed that the two units were closely comparable, and it was therefore concluded that they were suitable for use in the comparative system.

This paper presents the design details of the outdoor testing system used and the results of comparative testing of aluminum foil and aluminum paint with regard to their effectiveness as radiant barriers. Experimental results showed that the low-cost aluminum paint, although not as effective as aluminum foil, does have an enhancing effect on the thermal performance of the roof assembly system.

INTRODUCTION

This paper presents the results of investigations carried out to examine the effectiveness of passive design methods for improving the thermal performance of roof assemblies typical of unconditioned single-story domestic buildings, which form the largest group in the housing stock in the Caribbean. The high altitude of the tropical sun means that the domestic roof is the building element that receives by far the major portion of the incoming solar energy incident on the building. This, coupled with the small thermal capacitance of the typical domestic roof (corrugated galvanized steel sheeting with or without an uninsulated ceiling), identified this element as the one having the most significant effect on the indoor thermal conditions. With the primary focus on low-cost housing, any thermal enhancement strategy for the thermal performance of the roof has to be affordable to the low-income sectors of Caribbean society.

The main driving force for heat intrusion into the occupied space is absorbed solar energy at the external surfaces of the roof system. This can be significantly reduced by the use of solar reflective coatings on the sunlit roof surface, the cheapest and most effective method being whitewashing of the roof surface. Investigations have found that white building surfaces can reflect more than 75% of the incident solar energy (Reagan and Acklam 1979) and, due to a high emissivity, are capable of keeping the temperatures of sunlit surfaces close to that of ambient (Givoni 1981). Tests on sunlit galvanized steel specimens showed that two coats of gloss white paint kept the specimen temperature at about 40°C compared with 60°C for an untreated specimen surface. A major drawback of solar reflective roof surfacing is that it rapidly deteriorates due to dust and fungal and other discolorations. Koenigsberger et al. (1974) found that in the cases they examined in a typical tropical climate, corrugated steel, unless repeatedly painted by lime or white paint, was a very poor roofing material for tropical towns. The high maintenance requirement of a solar reflective roof coating makes it an unfeasible roof enhancement option.

Unpainted corrugated galvanized steel roofing attains temperatures in excess of 60°C during peak solar heating hours within the tropics. Because of the high thermal conductivity of steel and the nominal thickness of the sheeting, the internal and exposed surface temperatures are essentially equal. This high roof temperature creates a strong driving potential for heat intrusion into the occupied space. Reducing the amount of heat flow through the roof requires that the effective thermal resistance of the roof be

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increased. Bulk insulation is prohibitively expensive in the Caribbean. However, researchers have realized that most of the downward heat transfer from a heated cladding is via thermal radiation. Interest has therefore grown in the use of infrared radiation barriers (RBs) in the attic space of buildings. An RB consists of a low-emissivity or high-reflectivity surface (relative to thermal radiation), usually a polished aluminum foil surface (emissivity 0.05-0.15 [Saini 1980]) facing an air space. Generally, the cost of RBs is a fraction of the cost of bulk insulation, but downward heat transfer is reduced by as much as 40% (Fairey 1985; Hall 1986; Katipamula and O'Neal 1986; Levins et al. 1986; Ober 1988). RBs are, therefore, likely to provide the most cost-effective means of reducing heat intrusion via the roof.

Locally, the lack of foil for use in building applications meant that an alternative that is cheap and easily available had to be found. Aluminum paint (reflectivity 0.40-0.57 [Saini 1980]) has a significantly lower reflectivity than foil; however, the ease and relatively low cost with which a paint coating can be applied to the cladding underside, where dust accumulation is not significant, and evidence, from subjective response in the field, that aluminum paint reduces the radiant heat from the hot cladding make it an attractive option. To verify the effectiveness of RBs, two experimental rigs were designed and fabricated. Results of the testing carried out are presented here.

EXPERIMENTAL METHOD

Overview

An outdoor testing method was adopted for this experimental investigation of the thermal performance of the building roof assembly, since the response of enhancement strategies to ambient conditions as it affects an occupant of a building was the main concern. A system using two identical experimental units and parallel data acquisition for the two units was proposed for this investigation. One unit was used as a reference and remained unchanged during the test period. The various test configurations were set up in the second unit. This setup allowed the results of different tests to be correlated by considering the results relative to the reference unit. This method was used because of the transient nature of weather from day to day and the economic constraints that prevented the setting up and testing of all configurations simultaneously.

Both units were designed to represent the most commonly used domestic roofing system, consisting of a cladding of corrugated galvanized steel, an air space, and a ceiling of fibrous insulating material. The rig design allowed for the variation of both the cladding slope and the cladding/ceiling spacing.

Data on the total hemispherical insolation (incident solar energy on a surface) and on the temperature profile within the units were logged. The insolation was considered a key parameter, as it is a major contributor to the heating of sunlit surfaces not protected by shading, solar reflective surfacing, etc. Temperature was taken as a convenient criterion for the rating of the thermal performance of test configurations (Chandra 1980), since, from a comfort viewpoint, the interior surface temperatures of a building component dictate the amount of radiative heat to which the occupant is exposed.

Experimental Test Units

The test system used two similar roof assembly models. Each model was basically a timber-framed five-sided box on top of which the cladding was secured and inside of which a model ceiling was suspended. The frame of each box was 1.8 m long, 1.2 m wide, and 1.2 m high (see Figure 1). The sides and base of the box were insulated using 50-mm-thick expanded polystyrene boards to prevent unwanted heat transfer. This panelling also had the advantage of providing firm support between the framing members and preventing flapping of the tarpaulin used to weatherproof the sides of the boxes. The edges of the tarpaulin were secured to the frame of the units with wood strips and nails. At one of the 1.8 m by 1.2 m sides, screws were used to secure the wood strips to allow for access to the inside of the units.

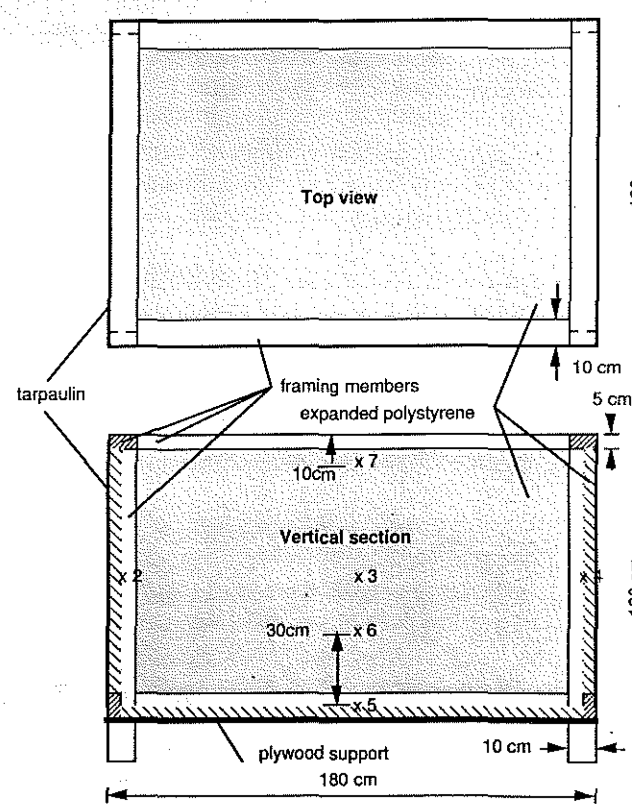

Figure 1 *Top view and vertical section of a test unit. Position of thermocouples within the unit is also indicated (x).*

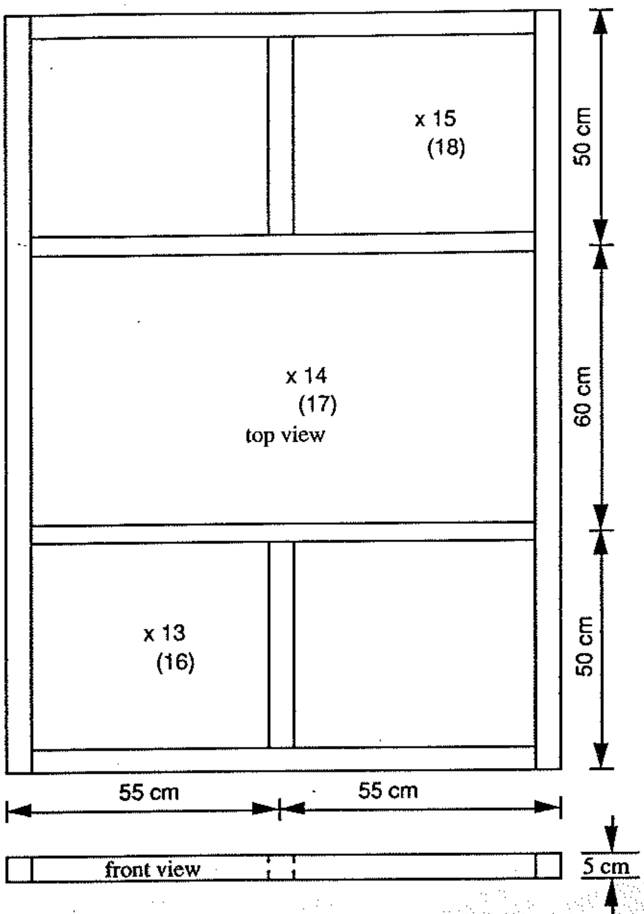

Figure 2 *Test ceiling frame. Relative thermocouple positions are also shown (x). Three thermocouples were located on either side of ceiling—13, 14, and 15 on the top surface and 16, 17, and 18 on the underside.*

The ceiling frames were 1.10 m by 1.6 m (see Figure 2). Grooved attachments at the corners allowed the frames to be suspended inside the boxes via plugs that fit into holes on the vertical framing members of the units and support the frames. The holes in the framing members of the unit were drilled at vertical intervals of 150 mm. This method also allowed the spacing of the ceiling from the cladding to be varied. These frames carried the different ceiling materials tested.

The Location and Setup of the Experimental Testing System

The experimental apparatus for this study was set up on the roof of a university's Mechanical Engineering Laboratory. The two experimental units were aligned in an approximate north-south direction as determined from position-fixing data. The northern ends of the units were raised 150 mm to allow for runoff of precipitation. The two units were 4 m to the east of a 2-m-high platform. Solarimeters were secured to the top of this platform with an instrument box containing the monitoring and data-logging equipment secured beneath it. Figure 3 shows a schematic of the experimental setup.

Corrugated, galvanized steel sheeting, aged to a dull finish, was nailed directly to the top of both units with commercially available galvanized roofing nails. The nails were used on the crests of the corrugated sheeting at 300-mm intervals. Aged sheeting was used in preference to new sheeting to avoid any change in the thermal performance characteristics of the surface of the sheeting when exposed to weather for a prolonged period. The referencing unit used a 20-mm-thick ceiling of expanded polystyrene ceiling tiles and a cladding/ceiling spacing of 300 mm. The material of the ceiling of the sampling unit was changed as required for the test conducted.

Changing of the Test Configuration

Three identical ceiling frames were constructed. One frame carried the control ceiling material and remained

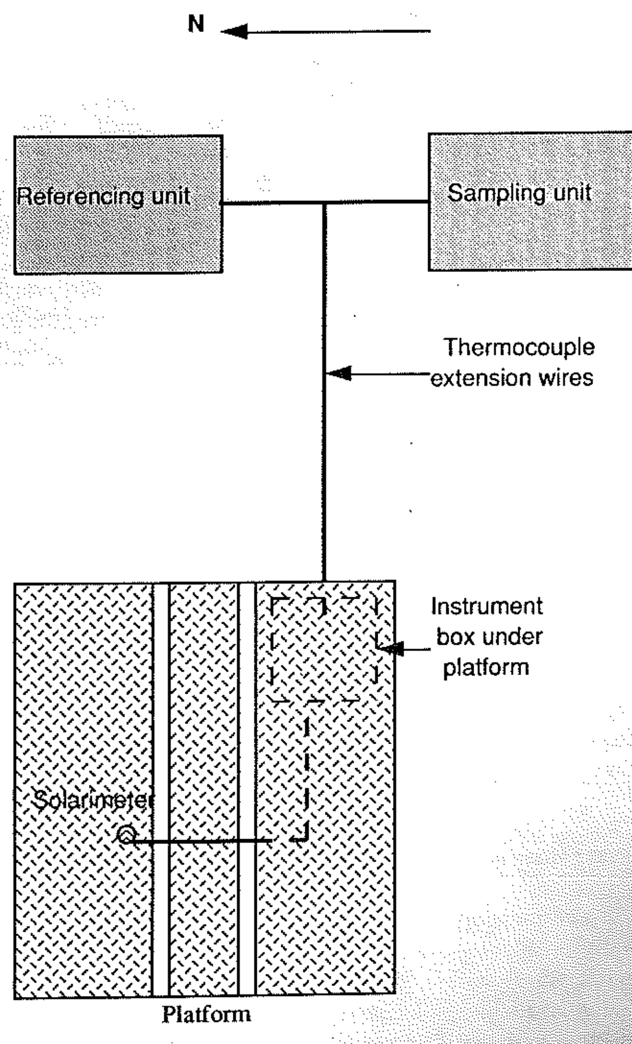

Figure 3 *Schematic plan view of experimental setup.*

unchanged in the control unit during testing. The other frames were used for the sampling unit. The ceiling frame not in use during a test was prepared in advance for the next test of the sequence. Table 1 shows the different configurations used for testing.

Changing the Test Ceiling In changing the test ceiling, the following procedure was adopted. The sampling rig was opened and the insulating expanded polystyrene was removed to expose the suspended ceiling in the unit. The four supporting pins were then removed and the ceiling removed. The alternate test ceiling was then set at the required position within the unit and secured with the pins.

The insulating expanded polystyrene was then replaced and covered with the tarpaulin, which was then secured by the wood strips and retaining screws to complete the setup.

Radiant Barrier (RB) Tests Two types of RBs were used to investigate the effects of reflective insulation on the roof assembly thermal performance. These were

1. aluminum foil (approximately U.S. \$0.40 per m^2) and
2. aluminum paint (two coats, approximately U.S. \$0.80 per m^2).

The above figures represent material costs and do not include labor. Aluminum foil-based RBs are the internationally available type of reflective insulation but are not locally available. To investigate the performance of the proposed aluminum paint RB relative to an RB comparable to those available internationally, an aluminum foil RB was made. The foil used is a commercially available product sold for kitchen applications. It is a thin, easily damaged sheet material with one surface bright and the other matt reflective. The matt side was glued onto thin, single-ply cardboard to produce a tough, manageable aluminum foil RB. For tests with this RB, the sampling unit was opened as described above and the RB was laid directly over the test ceiling material with the foil facing upward.

The aluminum paint RB consisted of two coats of a commercially available aluminum paint applied to the underside of the cladding of the sampling unit. The surface was first washed to remove grease and dirt and then the paint was applied by brush. In this manner, an attic containing an aluminum paint RB was made available for testing.

Instrumentation and Data Acquisition

Thermocouples were used in conjunction with commercially available digital equipment to monitor and log temperatures within the units. Also used were a commercially available solarimeter and integrator to provide insolation data. Temperatures and insolation data were logged simultaneously for both units at ten-minute intervals. From these data, the ceiling surface temperatures of the various test configurations were graded relative to the corresponding reference unit temperatures and the effect of the RB evaluated.

TABLE 1
Configurations Used with the Sampling Unit

Test	Ceiling Type	Radiant Barrier
1	A	None
2	B	None
3	C	None
4	D	None
5	B	aluminum foil
6	C	aluminum foil
7	D	aluminum foil
8	B	aluminum paint
9	C	aluminum paint
10	D	aluminum paint

A: 20-mm-thick expanded polystyrene tiles
B: 3-mm-thick decorative ply sheeting
C: 15-mm-thick grooved ply sheeting
D: 12-mm-thick mineral fiber tiles

The radiant barriers are described in the text. The above tests were conducted for a test cladding/ceiling spacing of 300 mm, which was identical to the spacing set in the referencing unit.

Temperatures were measured using k-type thermocouples that were all fabricated from the same spool of thermocouple wire (sensors were 1 m long). Surface-mounted thermocouples were supported along their length, against the surface being monitored, with an adhesive. The measuring junctions of the thermocouples attached to the metal cladding were soldered onto the surface. The junctions on nonmetallic surfaces were covered with a bead of grease to promote good thermal contact between the measuring junction and the surface. An internationally available, high-quality grade of thermocouple extension wire was used to connect the thermocouples to the electronic monitors located in the instrument box. One monitor was connected to a printer and instantaneous temperatures were logged at ten-minute intervals for the following sensors:

1. thermocouple 9, attached to the cladding underside (see Figure 4);
2. thermocouple 14, attached centrally to the upper surface of the ceiling (see Figure 2); and
3. thermocouple 17, attached centrally to the lower surface of the ceiling (see Figure 2).

A solarimeter (0.3 μm to 2.5 μm wavelength sensitivity) mounted on top of the outdoor platform was used to monitor the insolation levels during testing. It was connected to a commercially available printing integrator (accuracy $\pm 0.5\%$) in the instrument box under the platform. In this manner, integral values of the total hemispherical insolation on a horizontal surface were logged at ten-minute intervals over the test period.

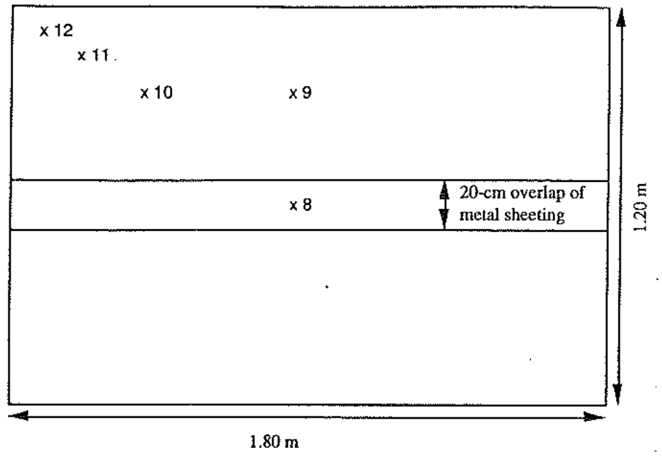

Figure 4 *Top view in plan showing the location of thermocouples on the underside of the cladding.*

Temperature Sensor Location within the Units

The locations of the thermocouples within the experimental units were as follows :

1. Thermocouples 8 to 12 were attached to the underside of the cladding as shown in Figure 4.
2. Thermocouple 7 was suspended 10 cm below the cladding as shown in Figure 1.
3. Thermocouples 13 to 18 were attached to the ceiling as shown in Figure 2.
4. Thermocouples 2 to 5 were attached to the inward-facing surfaces of the expanded polystyrene insulating panels as shown in Figure 1.
5. Thermocouple 6 was suspended 30 cm above the floor of the units as shown in Figure 1.

Null Testing of the Units

To compare the thermal performance of various test configurations with the reference unit, it was necessary first to establish that the thermal performance of the two units was closely related when investigated under similar physical conditions. A null test (test to investigate the thermal similarity of the test units) was therefore conducted with the sampling unit set up in a manner similar to the reference unit as described above. Temperature data were acquired simultaneously for the two units and the temperatures of the following surfaces compared: (1) cladding underside, (2) ceiling upper surface, and (3) ceiling lower surface.

Figure 5 illustrates that the temperature profiles of the two units bear a close relation. From the temperature profile of the ceiling's lower surface, the temperature that was used as the performance criterion for roof assembly testing, it can be seen that many common points exist between the reference and sampling temperature profiles, with a scattering of about 1°C. A similar variation for the ceiling's upper surface temperature profiles can also be seen. Therefore, at the ceiling level, the two units, when similarly set up, show very similar thermal performance characteristics.

The cladding's underside temperature profiles show only a few common points, with a scattering of 1-2°C. However, this difference is relatively small compared to the level of heating experienced by the cladding. Also, when taking into account the transient nature of the weather to which the cladding was directly exposed, along with the tendency of the thin metal cladding to react rapidly to weather changes, the agreement between the two profiles can be considered good.

The null test demonstrated that the units show good comparability and were therefore suitable for the side-by-side comparative testing proposed for this study.

RESULTS

Results of testing decorative ply (d, 3-mm-thick plywood with a decorative paper surfacing on one side), grooved ply (g, 15-mm-thick plywood with a typical grooved profile on one side), and mineral fiber (m) ceilings, plain and with an aluminum foil RB (f) and an aluminum paint RB (p) employed, are presented in Figures 6 to 8. Tests were run between August 1989 and May 1990 during which the monthly average maximum temperature varied between 30.0 and 32.9°C. The null test demonstrated that at the ceiling level, when identically set up, the units had approximately the same surface-temperature profiles. With only the attic/ceiling insulation being varied

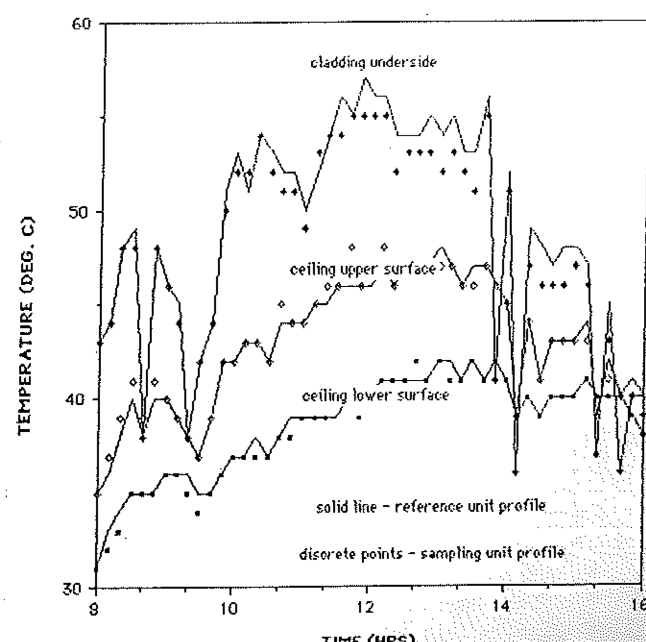

Figure 5 *Comparison of the temperature profiles for test units—null test results.*

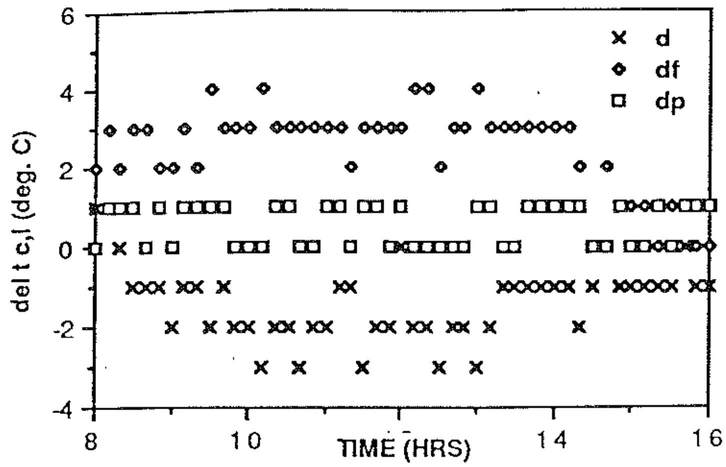

Fig. 6a
Decorative ply tests for the plain (d), aluminium foil (d,f) and aluminium paint (d,p) configurations.

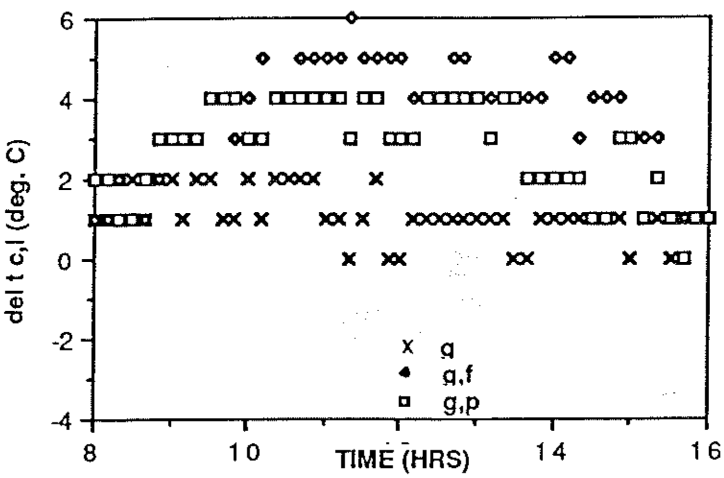

Fig. 6b
Grooved ply tests for the plain (g), aluminium foil (g,f) and aluminium paint (g,p) configurations.

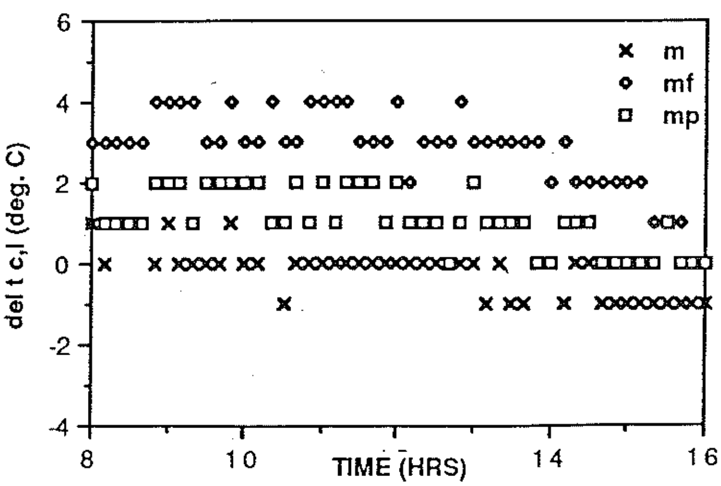

Fig. 6c
Mineral fibre tests for the plain (m), aluminium foil (m,f) and aluminium paint (m,p) configurations.

Figure 6 *Difference between temperature of the lower ceiling surfaces of the reference and sampling units (del $t_{c,l} = t_{c,l,r} - t_{c,l,s}$) vs. time.*

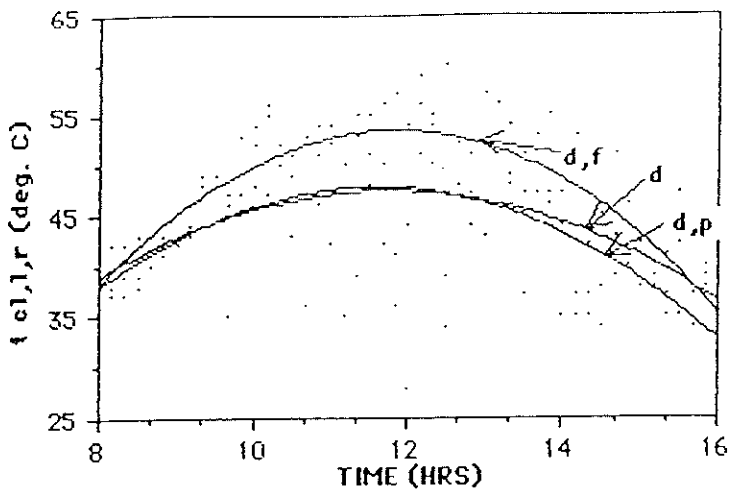

Fig. 7a

Decorative ply tests for the plain (d), aluminium foil (d,f) and aluminium paint (d,p) configurations.

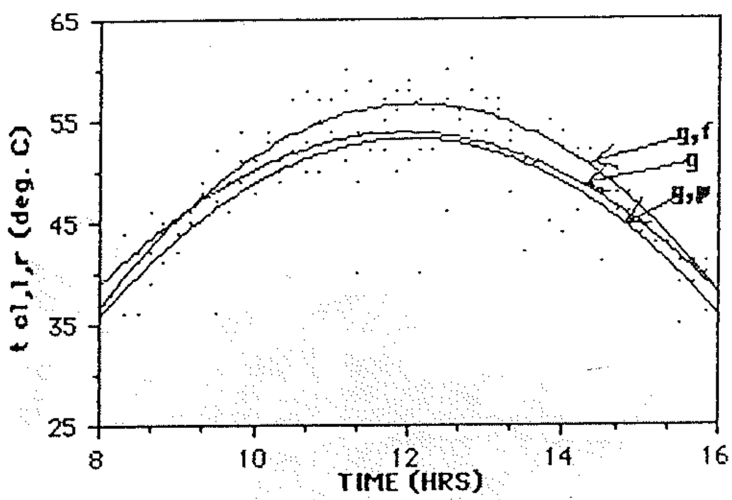

Fig. 7b

Grooved ply tests for the plain (g), aluminium foil (g,f) and aluminium paint (g,p) configurations.

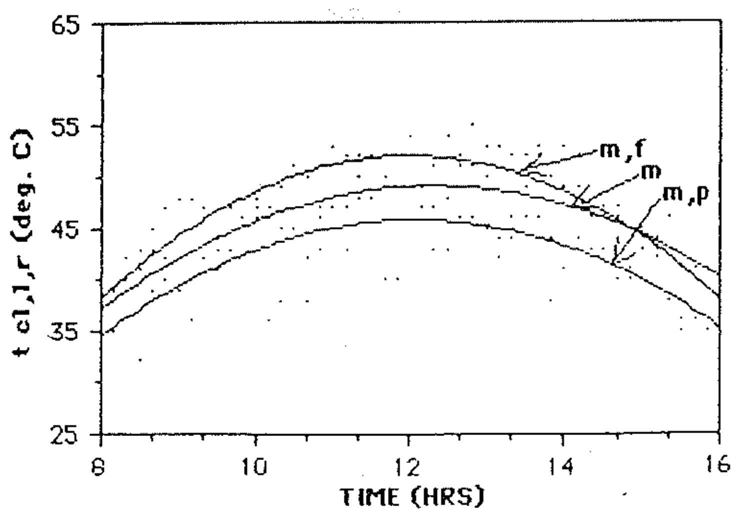

Fig. 7c

Mineral fibre tests for the plain (m), aluminium foil (m,f) and aluminium paint (m,p) configurations.

Figure 7 *Comparison of reference cladding temperature ($t_{cl,l,r}$) profiles for the performance testing of radiant barriers.*

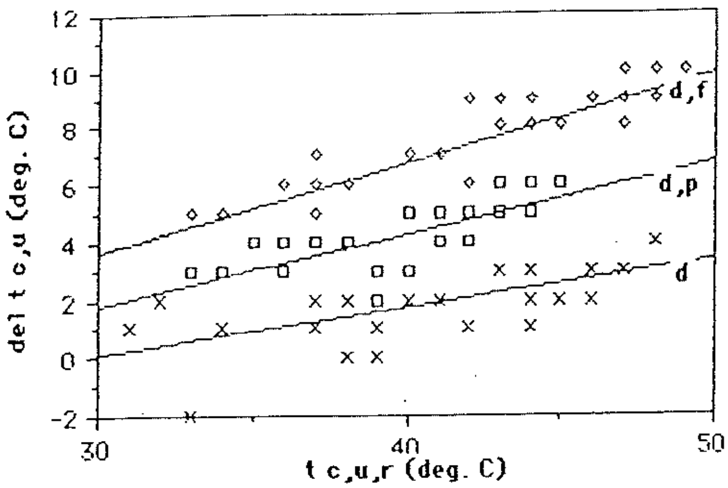

Fig. 8a
Decorative ply tests for the plain (d), aluminium foil (d,f) and aluminium paint (d,p) configurations.

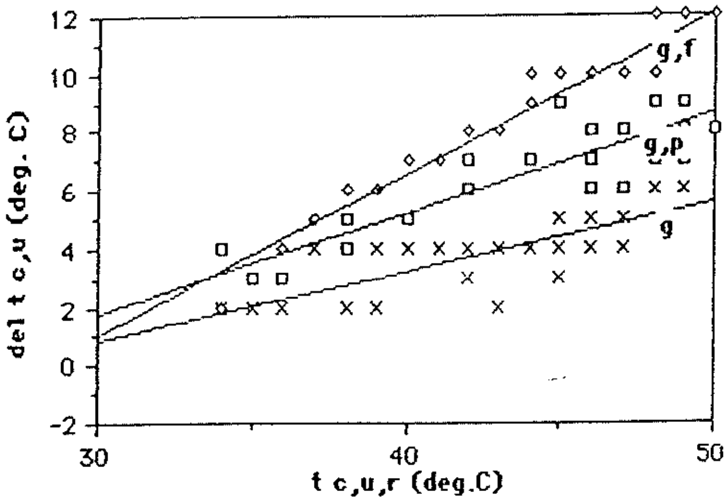

Fig. 8b
Grooved ply tests for the plain (g), aluminium foil (g,f) and aluminium paint (g,p) configurations.

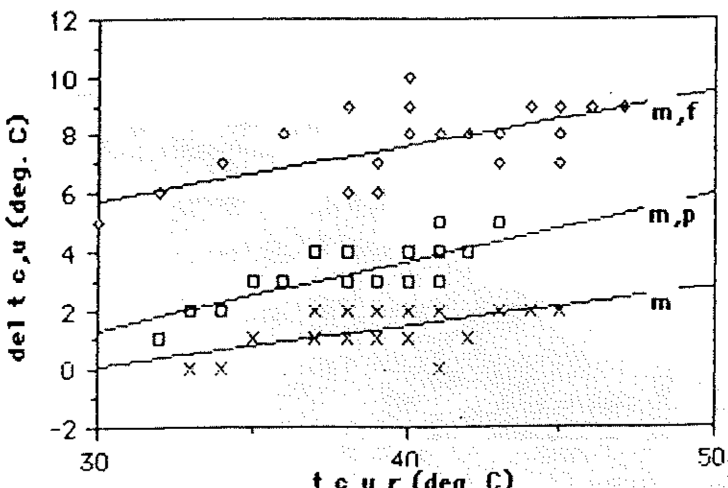

Fig. 8c
Mineral fibre tests for the plain (m), aluminium foil (m,f) and aluminium paint (m,p) configurations.

Figure 8 *Temperature difference between the upper ceiling surfaces of the reference and sampling units (del $t_{c,u}$ - $t_{c,u,r}$ – $t_{c,u,s}$) vs. reference ceiling's upper surface temperature ($t_{c,u,r}$).*

during testing, the reference unit's temperature profiles were taken as the datum. Therefore, by subtracting the sampling unit's ceiling surfaces temperatures from the simultaneous temperature values obtained for the reference unit, the thermal performance of the test configurations was graded as a temperature deviation from the unchanging reference. These graded values were then compared for the various tests.

Figure 6 shows the temperature difference (del $t_{c,l}$ = $t_{c,l,r}$-$t_{c,l,s}$) between the ceiling lower surface temperatures of the reference and sampling units vs. time for the plain and RB tests with decorative ply as ceiling (Figure 6a), grooved ply as ceiling (Figure 6b), and mineral fiber as ceiling (Figure 6c). For the corresponding tests of Figure 6, the reference cladding temperatures are compared in Figure 7. Because of the scattered nature of the cladding temperatures, best fit, second-order polynomial curves were used to compare their average nature. Differences in the heating levels and rates experienced during the various tests were assessed so that these could be taken into account in the discussion of the results presented in Figure 6.

The effect of RBs on the radiant heat transfer across the attic was also studied. The net radiant heat transfer across the attic results in an elevation of the ceiling's top surface temperature; therefore, the reduction in this temperature caused by the introduction of an RB provides an indication of its effectiveness. Figure 8 shows the temperature difference (del $t_{c,u}$ = $t_{c,u,r}$-$t_{c,u,s}$) between the upper surface temperatures of the reference and sampling ceilings vs. the reference ceiling's upper surface temperature ($t_{c,u,r}$). Therefore, relative to a given $t_{c,u,r}$, graded test ceiling temperatures were compared for the tests with and without RBs.

By definition of the temperature difference term, the larger its value, the lower is the test temperature relative to the reference unit temperature and, hence, the better is the thermal performance of the test configuration. This can be noted in Figures 6 and 8, where the aluminum foil test results consistently show higher values for the graded temperatures.

DISCUSSION

In an unconditioned building, the occupants exchange heat directly with internal building surfaces via thermal radiation. The building component parameter of interest is, therefore, the indoor surface temperature that dictates the level of this radiant exchange, all other factors being the same. A convenient criterion for the thermal performance of a component of an unconditioned building, as it impacts on the occupants, is, therefore, the temperature level attained by its indoor surfaces. For the roof assembly with a ceiling, this surface is that of the ceiling underside.

Figure 6a indicates that an aluminum foil RB reduces the underside temperature ($t_{c,l}$) of the decorative ply ceiling by about 5°C (maximum) when compared with the plain decorative ply test. The aluminum paint, on the other hand, reduces it by about 3°C (maximum). The cladding temperature profiles for these tests (Figure 7a) show that for the plain test and the test with aluminum paint, the temperatures are comparable. However, the aluminum foil test was done for conditions of greater ambient heating (6°C peak difference in cladding temperature). Foil results may therefore be slightly higher than if performed under milder ambient conditions similar to the other tests.

Figure 6b indicates that an aluminum foil RB reduces the underside temperature ($t_{c,l}$) of the grooved ply ceiling by about 4°C (maximum) when compared with the plain decorative ply test. The aluminum paint, on the other hand, reduces it by about 3°C (maximum). The average variation of the cladding temperatures obtained during these tests (Figure 7b) indicates that ambient heating conditions were similar during the tests with the unenhanced ceiling and the aluminum paint enhancement. However, for the test with the aluminum foil, the average cladding temperature variation peaked about 3°C higher with generally higher temperatures during the day.

Figure 6c indicates that an aluminum foil RB reduces the underside temperature ($t_{c,l}$) of the mineral fiber ceiling by about 4°C (maximum) when compared with the plain decorative ply test. The aluminum paint, on the other hand, reduces it by about 2°C (maximum). The average variation of the cladding temperatures obtained during these tests (Figure 7c) indicates that, relative to the plain test, the aluminum foil test experienced higher ambient heating conditions (about 3°C peak difference in cladding temperature) while the aluminum paint test experienced a reduced level of ambient heating (about 3°C peak difference in cladding temperature). Again, the aluminum foil test is seen to have been done during higher heating conditions than the other tests, and the results may be higher than expected relative to the plain and aluminum paint tests.

Therefore, the results indicate that both aluminum paint and aluminum foil RBs have a clear thermal performance enhancement potential for the roof assembly. The results further suggest that the performance of both types of barriers are similar when the ceiling's lower surface temperature is taken as the performance criterion.

The general effect of introducing a radiant barrier into the attic space can be seen in Figure 8. This figure shows the temperature difference between the referencing and sampling units for the upper surface of the ceiling (del $t_{c,u}$ = $t_{c,u,r}$ - $t_{c,u,s}$) for the various tests as a function of the temperature of the upper surface of the reference ceiling. The RBs are seen to increase this temperature difference significantly. This indicates that the low-emissivity surface of the RBs reduces the radiant heat transfer (the major transfer mechanism) across the air space, thus resulting in a reduction in the heating of the ceiling's upper surface. As noted in the introduction, researchers have found that RBs can reduce net roof assembly heat transfer by up to 40%.

In the case of the building without a ceiling, occupants are subjected to the high levels of radiant energy from the solar-heated cladding. The above results show that even a nominal ceiling, such as decorative ply, can act as a significant buffer in reducing radiant temperatures to building occupants. An RB consisting of a low-emissivity surface facing an air space can produce a similar effect. The RB greatly reduces the amount of radiant heat to which the occupant is exposed as well as the general rate of heating of the occupied space by reducing the rate of heat emission. This will provide for improved indoor thermal conditions.

CONCLUSIONS

The thermal enhancement potential of radiation barriers on a roof assembly typical of the Caribbean was investigated in this outdoor study. The null test demonstrated that the two experimental units were practically identical and therefore suitable for use in the side-by-side reference testing system proposed. By considering the temperature of the lower ceiling surface as the performance criterion of the roof assembly, the performance of aluminum paint was found to be closer to that of aluminum foil than their emissivity values would suggest. However, aluminum foil is clearly the more effective RB. Both options had an enhancing effect, as evidenced by the reduction in temperatures achieved at the lower ceiling surface. The aluminum foil reduced the radiant temperature at the ceiling's underside by reducing the amount of downward radiant heat transfer (via reflection) across the attic air space by about 4°C compared to 3°C for the aluminum paint, which reduced the amount of heat radiated from the underside of the hot cladding (due to a reduced surface emissivity) to the ceiling. Aluminum paint can therefore be considered a viable low-cost option as a reflective insulating layer in local domestic attics. Also, an advantage of aluminum paint is that on the cladding underside, dust accumulation is not significant, whereas, depending on the placement of aluminum foil radiant barriers, dust accumulation on their reflective top surface can be a significant drawback. It should be noted that radiant barriers affect the radiant heat transfer across an adjacent air space and such air spaces are therefore essential for their functioning.

NOMENCLATURE

d = decorative plywood ceiling material
f = aluminum foil RB test
g = grooved plywood ceiling material
m = mineral fiber ceiling material
p = aluminum paint RB test
RB = radiant barrier
t = temperature (°C)

Subscripts

c = ceiling
cl = cladding
l = lower surface
r = reference unit parameter
s = sampling unit parameter
u = upper surface

REFERENCES

Chandra, P. 1980. Rating of wall and roof sections—thermal considerations. *Building and Environment* 15: 245-251.

Fairey, P.W. 1982. Effects of infrared radiation barriers on the effective thermal resistance of building envelopes. ASHRAE SP38: 859-875.

Givoni, B. 1981. *Man, climate and architecture*. London: Applied Science Publishers.

Hall, J.A. 1986. Performance testing of radiant barriers. *Proceedings of the Third Annual Symposium on Improving Building Energy Efficiency in Hot Humid Climates*, Arlington, Texas.

Katipamula, S., and D.L. O'Neal. 1986. An evaluation of the placement of radiant barriers on their effectiveness in reducing heat transfer in attics. *Proceedings of the Third Annual Symposium on Improving Building Energy Efficiency in Hot Humid Climates*, Arlington, Texas.

Koenigsberger, O.H., T.G. Ingersoll, A. Mayhew, and S.V. Szokolay. 1974. *Manual of tropical housing and building*. Part 1: Climatic design. London: Longman.

Levins, W.P., M.A. Karnitz, and D.K. Knight. 1986. Cooling energy measurements of houses with attics containing radiant barriers. *Proceedings of the Third Annual Symposium on Improving Building Energy Efficiency in Hot Humid Climates*, Arlington, Texas.

Ober, D.G. 1989. Full scale radiant barrier testing Ocala, Florida: Summer 1988. *Thermal Performance of the Exterior Envelope of Buildings IV*, pp. 286-293. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Reagan, J.A., and D.M. Acklam. 1979. Solar reflectivity of common building materials and its influence on the roof heat gain of typical southwestern U.S.A. residences. *Energy and Buildings* 2: 237-248.

Saini, B.S. 1980. *Building in hot dry climates*. New York: Wiley.

BIBLIOGRAPHY

Abrantes, V. 1985. Thermal exchanges through ventilated attics. *Proceedings of the Third Annual Symposium on Improving Building Energy Efficiency in Hot Humid Climates*, Arlington, Texas.

Baker, N.V. 1987. *Passive and low energy design for tropical island climates*. London: Commonwealth Secretariat.

Barned, J.R. 1970. Thermal conductivity of building materials. Commonwealth Scientific and Research Organisation, Report R.2: 28-29. Victoria: Commonwealth Scientific and Research Organisation.

Cook, J.C., D.W. Yarbrough, and K.E. Wilkes. 1989. Contamination of reflective foils in horizontal applications and the effect on thermal performance. Tennessee: Oak Ridge National Laboratory.

Courville, G.E., and J.V. Beck. 1988. Measurement of field thermal performance parameters of building envelope components. *ASHRAE Transactions* 94(2): 1595-1612.

Fairey, P.W. 1982. Effects of infrared radiation barriers on the effective thermal resistance of building envelopes. ASHRAE SP38: 859-875.

Grot, R., M. Modera, J.B. Fang, and H. Park. 1985. Instrumentation for the in situ measurement of building envelopes. *ASHRAE Transactions* 91(2B): 1088-1099.

Hedlin, C.P. 1985. Calculation of thermal conductance based on measurements of heat flow rates in a flat roof using heat flux transducers. ASTM STP885: 184-202. Philadelphia: American Society for Testing and Materials.

Lippsmeier, G. 1969. *Building in the tropics*. Munchen: Callwey Verlag.

McIntyre, D.A. 1985. In situ measurement of U-values. *Building Services Engineering Research and Technology* 6(1): 1-6.

Nayak, J.K., A. Shrivastava, U. Singh, and M.S. Sodha. 1982. Different approaches to the passive cooling of roofs. *Building and Environment* 17(2): 145-161.

Olgyay, V. 1963. *Design with climate*. Princeton, NJ: Princeton Press.

Roberts, C.C., and K. Reinke. 1982. Thermal measurements of building envelope components in the field. *ASHRAE Journal* 24(3): 35-39.

Stewart, W.E., B.R. Becker, L.A. Stickler, and M.E. Greer. 1989. Approximate attic air temperatures and ceiling heat fluxes with radiant barriers. University of Missouri.

Wilkes, K.E. 1989. Model for roof thermal performance. Document ORNL/CON-274. Tennessee: Oak Ridge National Laboratory.