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Measured Performance of Ten Roof Assemblies in a Hot, Arid Climate

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ABSTRACT

Ten roof assemblies of varying structural and insulative configuration were designed, constructed, instrumented, and monitored at a test facility in Dhahran, Saudi Arabia. The monitoring activities were carried out in support of a larger-scale project to evaluate the thermal and economic performance of insulated constructions for Saudi buildings. The roof configurations selected for investigation generally represent the types of massive construction common to the Middle East. Documenting the performance of alternative insulation approaches for such constructions, especially insulation position within the roof assembly, was a key objective of the research. Temperature and heat flow data were recorded every 15 minutes during the duration of the tests. This paper presents selected temperature and heat flow measurements for the ten roof panels recorded during the first ten weeks of monitoring activity with an emphasis on performance under summerlike weather conditions.

INTRODUCTION

Buildings in Saudi Arabia have historically utilized a combination of passive cooling techniques, such as radiative cooling and natural ventilation, coupled with the capacitive insulation effects of massive construction assemblies to provide some degree of control over interior thermal conditions. Rapid economic development in the country has led to the construction of a phenomenal number of new buildings (both residential and commercial) during the past 10 years. In response to the severe summer weather conditions experienced throughout most of Saudi Arabia, these newer buildings are universally cooled by means of mechanical refrigeration systems. Resistive thermal insulation materials are not normally used in Saudi construction—either for roof or wall assemblies. Although some thermal benefit is likely gained from the contemporary use of massive building envelope elements, the energy burden imposed by the continued construction of a thermally inefficient building stock is of concern to the Saudi government.

A comprehensive three-year research program to investigate the thermal and economic viability of potential insulation approaches for Saudi buildings was developed and implemented. A portion of this research effort was intended to provide actual in-situ thermal performance results for a number of representative roof assemblies. To this end, a test facility containing ten roof panels with different construction and insulation details was built in Dhahran, Saudi Arabia. Field-test data derived from operation of this facility will be compared with performance projections for the various roof assemblies derived through the use of the DOE-2 computer modeling program. Life-cycle cost analyses of proposed insulation approaches will also be undertaken to assess the economic worth of thermally promising roof assemblies.

Dhahran, site of the roof test facility, is located in the Eastern Province of Saudi Arabia at a latitude of roughly 26° north and a longitude of 50° east. The facility is situated at an elevation of around 130 ft (40 m) above sea level. The Eastern Province, typical of the majority of Saudi Arabia, is an exceptionally arid region, receiving less than 3 in. (75 mm) of rainfall in an average year, with virtually none during the summer (essentially between the months of April and November). Dhahran's proximity to the Arabian Gulf, however, provides for a surprisingly humid environment at times. The ASHRAE (1981) 1% summer design dry-bulb temperature for Dhahran is 111°F (44°C) with a coincident wet-bulb temperature of 81°F (30°C). The summer outdoor daily temperature range of 32°F (18°C) is of a magnitude appropriate to a hot, arid climatic zone. The 99% winter design dry-bulb temperature for Dhahran is given as 45°F (7°C). Barkat Ullah et al. (1982) indicate that Dhahran experiences virtually no cloud cover during the months of May through October, with summer midday solar radiation values typically around 300 Btu/h·ft^2 (1000 W/m^2). Maximum mean temperatures of 86.7°F (30.4°C) for April and 97.2°F (36.2°C) for May are reported by the same authors.

ROOF CONFIGURATIONS

As may be inferred from the climatic data presented above, building thermal design efforts in most of Saudi Arabia tend to focus on the issue of cooling; heating is of substantially less concern. Vernacular buildings have been constructed of massive materials (such as stone) to provide some capacitive insulation benefit. Flat roofs have traditionally been used in both residential and commercial buildings, providing additional living space (as an outdoor "terrace") and the potential for nighttime convective and radiative cooling.

Modern building design and construction practices tend to mirror the old traditions, with massive wall and roof assemblies the elements of choice for both residential and commercial buildings. Typically, roofs in contemporary

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buildings are of poured-in-place concrete. Roof constructions employing conventional (homogeneous) concrete slabs and hourdi-block slabs (concrete slabs with a filler of concrete block or hollow clay tile) are both popular, with distinct regional preferences for one "style" of slab versus another. Various waterproofing materials are used with these roof constructions. Although the Saudi climate is arid, seasonal rains cause leakage problems in many buildings due to poor drainage, improperly installed and detailed waterproofing membranes, and deterioration of waterproofing materials.

The use of resistive insulation in roof and wall assemblies is not the norm in contemporary design and construction practice. There are likely two main reasons for this. The first is the exceptionally low cost of electricity to the consumer (on the order of a third that found in most areas of the United States). Thus, "adding" insulation to a building design must be justified on the basis of life-cycle cost rather than an instinctive feeling of economic appropriateness. The second has to do with the lack of resistive insulation use in traditional building examples,which form the historical basis for many modern building decisions. Building codes are being promulgated to shift designers and owners toward the inclusion of insulation elements, but which approaches are most appropriate to the Saudi setting is still an open issue.

Ten roof assemblies were selected for in-situ performance evaluation as part of this project. Summary descriptions of these ten assemblies are presented in Table 1. Roof 1 and roof 6 represent the types of uninsulated roof assemblies found in buildings throughout Saudi Arabia. These two roof constructions serve as references for the performance of the insulated alternative roofs designed for this project. Roofs 2, 5, 7, and 8 provide various insulation approaches to test the issue of insulation location within the assembly sandwich. Roof 9 represents a lightweight structural alternative, included to compare massive versus lightweight construction approaches with particular reference to the Saudi context. Roofs 3, 4, and 10 were included to examine material, waterproofing, and structural alternatives, respectively.

With the exception of roof 9 (that had an exposed waterproofing membrane), all roofs were topped off with a layer of sand, a mortar bed, and a white terrazzo tile walking surface. Roof 9 quickly collected a buff-colored layer of dust that might be characterized as a medium-color roof finish. The other roofs, topped with "slick" terrazzo tiles, remained reasonably clear of dust due to wind action and maintained an off-white, highly reflective finish. With the exception of roofs 8 and 9 (which included suspended ceilings), all roofs had an interior ceiling finish of white-painted cement plaster applied directly to the structural slab. All ten roof assemblies are intended to function as flat roofs and were installed in a horizontal position. Figures 1 through 10 illustrate the construction of the roof panels to provide an understanding of the nature of the assemblies being discussed.

As noted in Table 1, three resistive insulation materials were included in the roof panel assemblies monitored for this project. Roof panels 1 and 6 were uninsulated in the conventional sense, employing only capacitive thermal elements. Roof panels 2, 4, 5, 7, 9, and 10 utilized extruded polystyrene board insulation. Roof panel 3 utilized polyurethane board insulation, while roof panel 8 utilized glass fiber batt insulation. All insulation materials were provided by local suppliers and were assumed to represent "new" stock. Guarded hot plate testing (which was carried out at the time of panel construction at 95°F [35°C] mean temperature—believed to be in keeping with local conditions) gave thermal conductivity results consistent with published manufacturers' data for aged materials: 0.018 Btu/h·ft·°F (0.032 W/m·°K) for extruded polystyrene, 0.027 (0.033) for glass fiber batt, and 0.014 (0.024) for polyurethane samples.

THERMAL MEASUREMENTS

An existing building located on a flat, open site on a university campus was converted into a research facility with provision for 14 wall and 10 roof test panels. The roof panels were installed in an addition to the existing building, which was constructed specifically for use with the project. The dimensions of the individual roof test panels vary slightly to accommodate the dimensions of this supporting facility. A typical panel, however, is approximately 6.5 ft (2 m) long by 3.3 ft (1 m) wide—dimensions considered more than adequate to provide for heat flow patterns representative of full-scale installations. The thickness of any particular assembly is a function of construction type and insulation detail.

The roof test panels are contiguous (although separated from one another by strips of vegetable-fiber sheathing to reduce thermal contact) and together form the roof of one room in the test facility. To the extent possible, the panels were installed using conventional construction practices with local building trade labor. The roof panels are surrounded by a short insulated parapet, which provides some self-shading (identical for all panels) during portions of the day. There are no trees or adjacent buildings, however, to cause additional shading.

In general, the temperature and heat flow measurement approaches, sensors, and installation techniques utilized in this effort were based on experiences previously reported by researchers engaged in similar investigations. Insights provided by Flanders (1985a, 1985b), Hedlin (1985), Fang and Grot (1985), Grot et al. (1985), Shu et al. (1981), and Kuehn (1982) were especially germane to the instrumentation and monitoring requirements of this project.

Temperatures at numerous locations in, on, and around the roof panels were measured using type-T thermocouples. A temperature profile across each roof panel was established through a line of thermocouples, each line consisting of one thermocouple installed on the interior surface of the panel, another installed in the same relative location on the

TABLE 1
Description of Roof Assemblies

Roof No.	Basic Structure	Insulation	Location	Remarks
1	10 in. (250 mm) reinforced concrete slab	uninsulated	n/a	typical contemporary roof design, used as control
2	10 in. (250 mm) reinforced concrete slab	3 in. (75 mm) extruded polystyrene	above slab	insulated variant of roof 1, insulated external to mass
3	10 in. (250 mm) reinforced concrete	3 in. (75 mm) polyurethane board	above slab	insulation material variant of roof 2
4	10 in. (250 mm) reinforced concrete	3 in. (75 mm) extruded polystyrene	above slab	protected membrane (PMR) version of roof 2
5	10 in. (250 mm) reinforced concrete	2 in. (50 mm) extruded polystyrene	below slab	insulated variant of roof 1, insulated internal to mass
6	10 in. (250 mm) hourdi-block slab	uninsulated	n/a	hourdi-block variant of roof 1
7	10 in. (250 mm) hourdi-block slab	3 in. (75 mm) extruded polystyrene	above slab	insulated variant of roof 6, insulated external to mass
8	10 in. (250 mm) hourdi-block slab	4 in. (100 mm) glass fiber batt with air space	below slab	internally insulated variant of roof 6; 4 in. (100 mm) air space
9	corrugated metal deck (no concrete)	3 in. (75 mm) extruded polystyrene	above deck	light-weight roof system alternative
10	8 in. (200 mm) hollow-core concrete planks	3 in. (75 mm) extruded polystyrene	above planks	manufactured alternative to poured-in-place

Note: refer to Figures 1 through 10 for sections through roof assemblies.

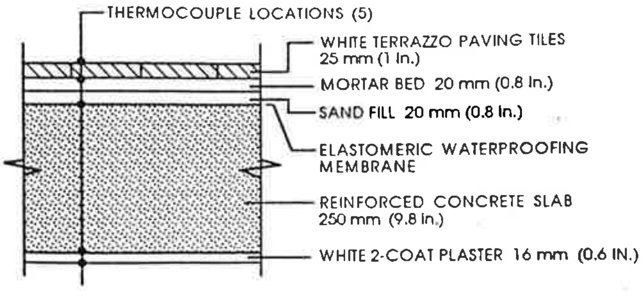

Figure 1 *Roof 1: uninsulated poured-in-place concrete slab.*

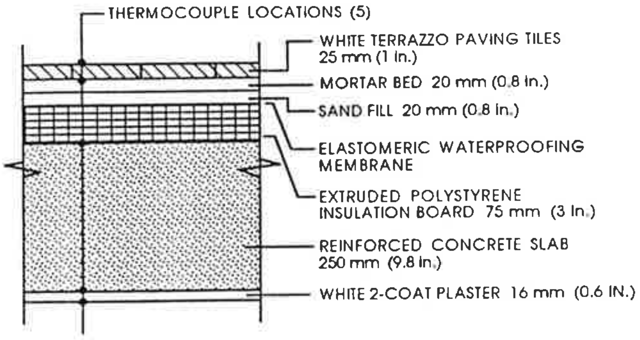

Figure 2 *Roof 2: externally insulated (extruded polystyrene) concrete slab.*

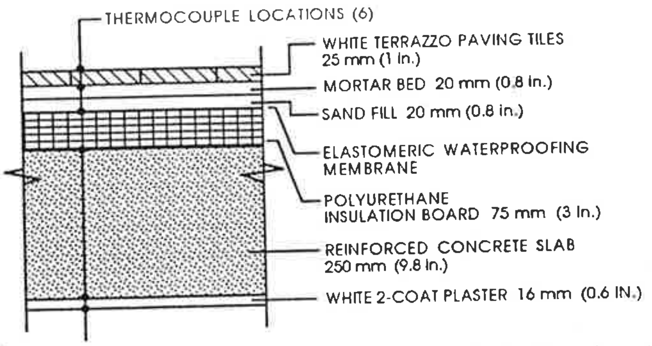

Figure 3 *Roof 3: externally insulated (polyurethane) concrete slab.*

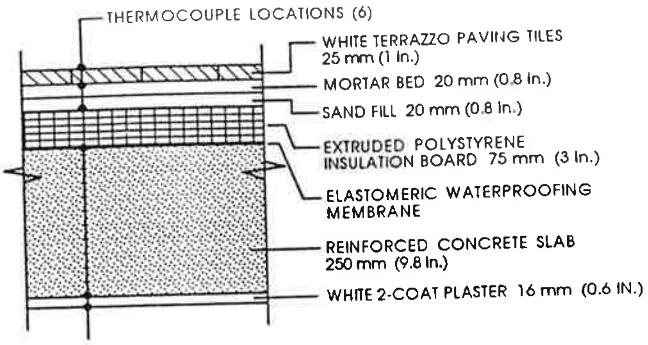

Figure 4 *Roof 4: protected membrane (extruded polystyrene) concrete slab.*

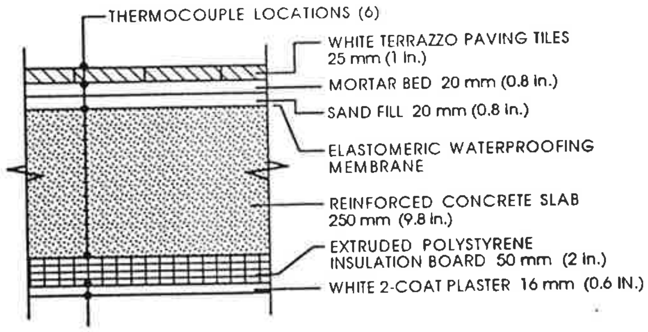

Figure 5 *Roof 5: internally insulated (extruded polystyrene) concrete slab.*

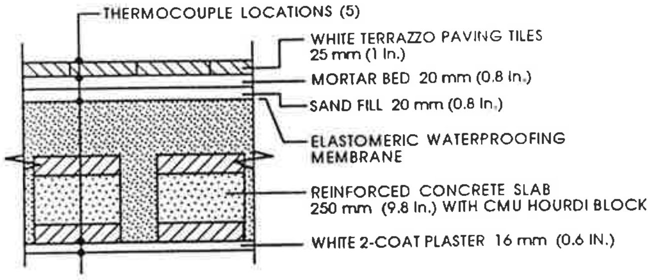

Figure 6 *Roof 6: uninsulated hourdi-block concrete slab.*

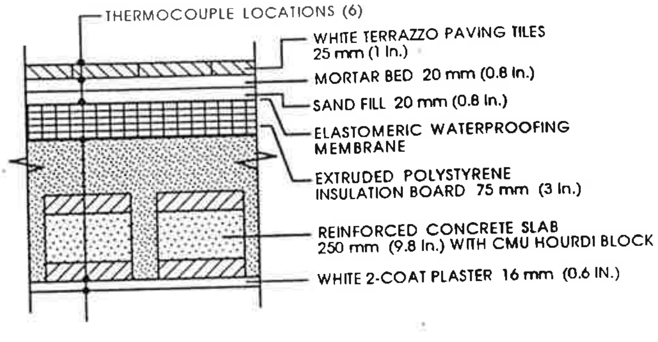

Figure 7 *Roof 7: externally insulated (extruded polystyrene) hourdi slab.*

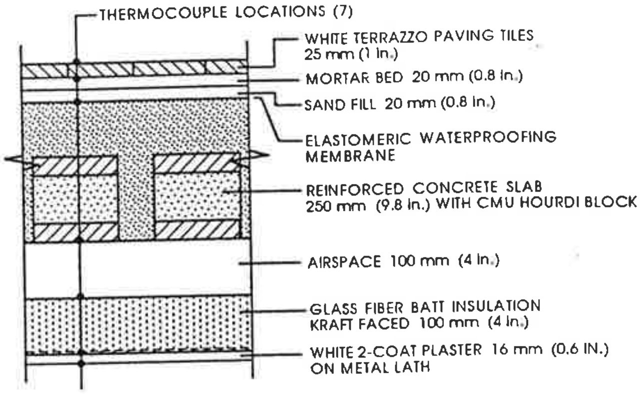

Figure 8 *Roof 8: internally insulated (glass fiber) hourdi slab.*

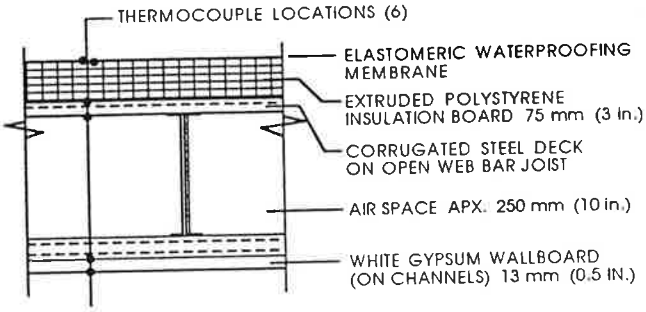

Figure 9 *Roof 9: insulated (extruded polystyrene) metal deck*

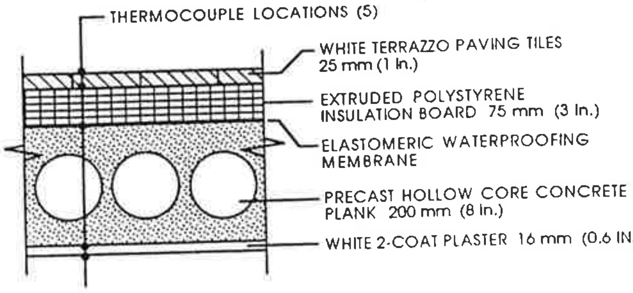

Figure 10 *Roof 10: externally insulated (extruded polystyrene) concrete planks.*

exterior surface of the panel, and additional thermocouples installed at each material junction within the assembly (as noted in Figures 1 through 10). Each thermocouple line is placed near the mid-point of its respective roof panel. The commercially manufactured thermocouples were installed using a highly conductive "thermal" adhesive. Additional thermocouples are employed to measure interior air temperatures within the test facility and ambient external air temperatures surrounding the building. Solar radiation measurements were not included as part of this project, although such measurements are made at a research institute located less than 1 mile (0.5 km) from the test facility. Typical monthly solar radiation intensities for Dhahran have been reported by Barkat Ullah et al. (1982).

Heat flow through the ten roof panels was measured via interior surface-mounted heat flow meters. The commercially manufactured meters, placed in the center of the respective panels, are 2 in. by 2 in. (50 mm by 50 mm) and were installed using white plastic tape to emulate the absorbtance and emittance of the white-painted plaster (or drywall) ceilings used with all roof assemblies. It was necessary to spackle and sand several of the ceiling surfaces in order to get a sufficiently smooth surface to which the heat flow meters could be attached. It was also found to be necessary to check meter installation on a regular basis to ensure that the bond between the mounting tape and the ceiling had not loosened. Tape was replaced as required (roughly every two months) as bonding weakened; replacement was done in a manner that would not modify the location of the meter relative to the panel.

Temperature and heat flow data were collected and stored every 15 minutes through use of a computer-based data acquisition system. Data were written to disk storage in real time. Data files were subsequently retrieved and were reviewed and processed using a commercial spreadsheet program, which was also employed to provide graphic analysis of selected data. The size of the data files was cause for concern in the transition from ASCII file format to packaged software format; this transition, however, was accomplished through use of a commercially available file manipulation program. The test facility was climate controlled with window air-conditioning units (commonly used in Saudi buildings) to approximate the interior conditions likely to be found in a residence. Although interior and exterior relative humidity was not continuously monitored, interior relative humidities typically ranged from 40% to 60%. Interior temperature fluctuated with load and air-conditioning unit cycling but was normally between 73°F and 79°F (23°C - 26°C). The test building was entered on a daily basis for system servicing and inspections but was not "lived in."

The primary purpose of the test facility measurements described herein is to provide verification (in the context of Saudi climate and construction practices) of roof assembly performance predictions independently generated by DOE-2 simulations. Thus, specific details of heat transfer through the various roof assemblies was not of as much concern as patterns of relative performance from one alternative to another. In order to obtain a reasonable picture of such performance, the in-situ monitoring program was scheduled to run for one consecutive year. The results reported in this paper are extracted from the first 10 weeks of collected data (March 16, 1990, through May 24, 1990), which were analyzed prior to the Kuwait conflict.

RESULTS

Data collected during the week of May 18-24, 1990, are considered representative of typical summer performance although only a brief period of time is actually involved. The weather during this one-week period was sunny, clear, and hot. Maximum outside air temperatures of 104°F to 111°F (40°C - 44°C) were typical during the week. The two weeks prior to the week of May 18-24 were also hot and generally sunny, leading to reasonably stable thermal conditions during the week in question. At the time these data were collected, the facility and data collection activities had been in operation for more than three months, with only occasional short-term outages for repairs or power failures.

Table 2 provides a summary of heat flow through the ten roof panels for the week of May 18-24, 1990. A total of 670 measurements was made for each roof. The maximum and minimum recorded heat flow values are "spot" occurrences; a positive value references heat gain (from exterior to interior) and a negative value indicates a heat loss (however tenuous). The total heat flow is the sum of the absolute value of all 670 recorded heat flows during the period and represents a direction-neutral measure of heat flux through the ceiling plane of each roof assembly. Net heat flow, perhaps the best "figure of merit" for roof performance during the summer season, represents the total recorded heat gain through the roof (during the week) less the total heat loss. The total and net heat flows shown in Table 2 have not been integrated over time and for that reason are presented with the units indicated.

Figure 11 provides a graphic comparison of net heat flow through the ten roofs during this one week of summer-like weather. As might be expected, the uninsulated "homogeneous" concrete slab roof assembly (roof 1) exhibited the worst thermal performance (permitting the highest heat gain to the building). The insulated lightweight roof (roof 9) and the uninsulated hourdi-block slab (roof 6) exhibited similar net heat flow totals over this one week period, although both roofs presented substantially better performance than the uninsulated roof (roof 1). The lower slab conductivity afforded by the hourdi-block fill is presumably to account for the almost 50% reduction in heat flow as compared to the uninsulated "homogeneous" slab (roof 1). The best overall performance was shown by roofs 5 and 2, both of which are concrete slab constructions, roof 5 being internally insulated with 2 in. (50 mm) of extruded polystyrene insulation and roof 2 being externally insulated with 3 in. (75 mm) of the same insulation material. Table

TABLE 2
Heat Flow Summaries for Roof Panels Week of May 18-24

Roof No.	Maximum Heat Flow	Minimum Heat Flow	Total Heat Flow	Net Heat Flow
1	16.7 (52.7)	3.5 (10.9)	5713 (17996)	5713 (17996)
2	4.3 (13.6)	-0.3 (-0.8)	1096 (3452)	1096 (3451)
3	4.4 (13.9)	-0.8 (-2.6)	1368 (4308)	1358 (4279)
4	5.6 (17.7)	-0.6 (-2.0)	1368 (4312)	1361 (4288)
5	4.4 (13.8)	-0.1 (-0.2)	1001 (3152)	1001 (3152)
6	8.1 (25.4)	1.8 (5.8)	3312 (10433)	3312 (10433)
7	4.3 (13.6)	0.5 (1.7)	1732 (5455)	1732 (5455)
8	5.6 (17.5)	1.0 (3.2)	2443 (7695)	2443 (7695)
9	13.2 (41.6)	0.1 (0.3)	3511 (11059)	3511 (11059)
10	5.2 (16.3)	-1.1 (-3.4)	1486 (4681)	1465 (4614)

Note: heat flow expressed as Btu/h·ft^2 (W/m^2)

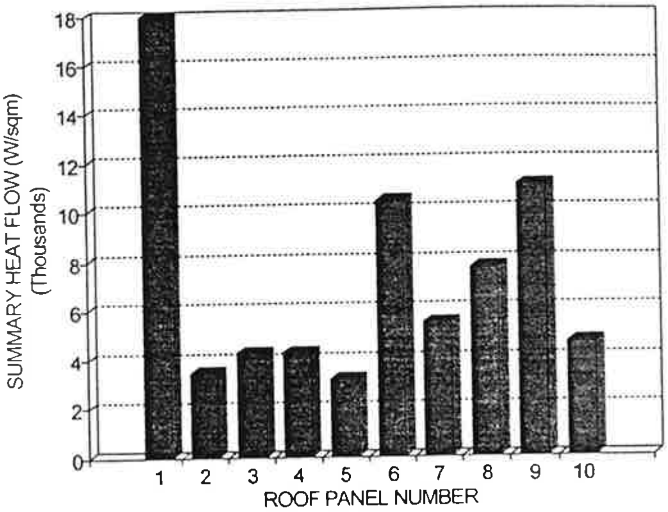

Figure 11 *Comparison of weekly net heat flow for ten roof assemblies.*

3 summarizes the heat flow performance of all ten roof assemblies.

Representative temperature profiles through three of the roof assemblies are presented in Figures 12, 13, and 14. These profiles are for a 12-hour period (midnight to noon) on May 16, 1990 (a hot sunny day). The effect of a darker roof surface may be clearly seen by comparing external surface temperatures for roof 9 (dust-covered waterproofing membrane) with those for roof 2 (light terrazzo tile finish) —a difference of 36°F (20°C) in peak temperatures is noted. The effect of insulation location on temperatures throughout an assembly may be seen by comparing exterior and interior surface temperatures for roof 2 (external insulation) and roof 5 (internal insulation). The exterior peak temperature is approximately 9°F (5°C) higher for the externally insulated roof. Interior surface temperatures (heavily influenced by room air temperature and of concern with respect to occupant thermal comfort) are virtually the same for both roof constructions.

CONCLUSIONS

Although it is not advisable to extrapolate from the limited data from this project that have been analyzed to date, it is reasonable to suggest several trends. Obviously, uninsulated concrete slabs are not desirable if energy conservation is a design objective; all nine alternative roof assemblies outperformed the control roof (the uninsulated homogeneous concrete slab, roof 1) under summerlike weather conditions. Substantial thermal benefit may be gained from use of hourdi-block slab construction as opposed to a "monolithic" slab approach. This is an interesting finding in light of the difficulty typically encountered in establishing appropriate thermal properties to permit accurate modeling of such a composite construction. In the Saudi climatic regime, lightweight roof assemblies (such as roof 9) will apparently need to provide substantially better thermal resistance than assumed for this testing program if they are to compete with the more traditional massive construction approaches. It is probable that, provided there is an easily maintained, highly reflective external finish, a lightweight roof approach might fare better than demonstrated in this project, although the benefits of thermal mass in the Dhahran summer climate seem substantial.

The location of insulation within an assembly does appear to make a difference in terms of thermal performance. Roof 5, with 2 in. (50 mm) of extruded polystyrene insulation placed internal to the mass of the assembly, provided equal thermal performance to roof 2 with 3 in. (75

TABLE 3
One-Week Summary of Heat Flow for Ten Roof Assemblies
(Ranked in increasing order of performance)

Roof No.	Weekly Net Heat Flow	% of Roof 1	Construction Summary	Thermal Resistance Insulation	Thermal Resistance Total
1	5713 (17996)	100	unins. slab	0.0 (0.0)	4.1 (0.7)
9	3511 (11059)	61	ins. metal deck	13.4 (2.4)	16.6 (2.9)
6	3312 (10433)	58	unins. hourdi	0.0 (0.0)	4.3 (0.7)
8	2443 (7695)	43	hourdi w/ batt	12.2 (2.2)	17.4 (3.1)
7	1732 (5455)	30	hourdi ext. ins.	13.4 (2.4)	17.7 (3.1)
10	1465 (4614)	26	hollow core	13.4 (2.4)	15.6 (2.8)
4	1361 (4288)	24	slab ext. ins.	13.4 (2.4)	17.5 (3.1)
3	1358 (4279)	24	slab ext. ins.	18.1 (3.2)	22.2 (3.9)
2	1089 (3451)	19	slab ext. ins.	13.4 (2.4)	17.5 (3.1)
5	1001 (3152)	18	slab int. ins.	8.9 (1.6)	13.0 (2.3)

Note: heat flow expressed as Btu/h·ft^2 (W/m^2)
thermal resistance expressed as ft^2·h·°F/Btu (m^2·°C/W)

mm) of the same insulation material placed external to the mass of the assembly. (As a sidelight, the difference in insulation thickness between these two roof assemblies was the result of a construction error, perhaps leading to a more interesting comparison than originally intended.) All of these preliminary conclusions are based on measurements conducted under high exterior temperatures in a clear sky, high solar radiation environment. Different patterns of performance were noted under cooler conditions.

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REFERENCES

ASHRAE. 1981. *ASHRAE Handbook—1981 Fundamentals*, p. 24.21. Atlanta: American Society of Heating,

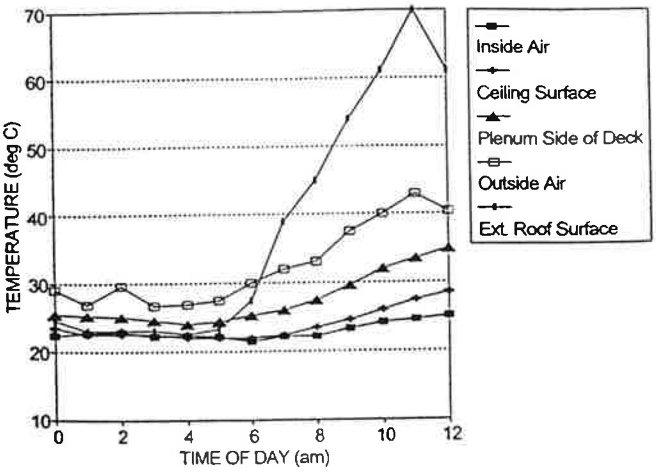

Figure 12 *Roof 9: twelve-hour temperature profile for May 16, 1990.*

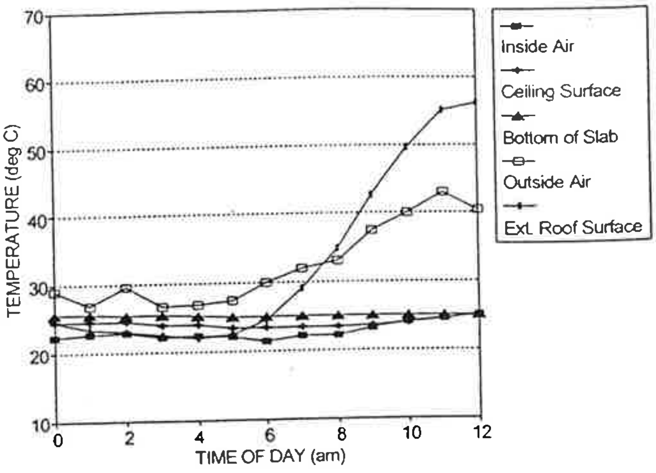

Figure 13 *Roof 2: twelve-hour temperature profile for May 16, 1990.*

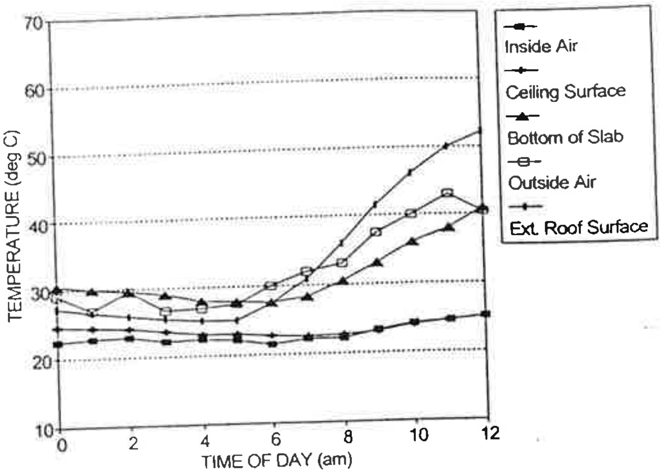

Figure 14 *Roof 5: twelve-hour temperature profile for May 16, 1990.*

Refrigerating and Air-Conditioning Engineers, Inc.

Barkat Ullah, M., W. Al-Harari, and H. Benson. 1982. An analysis of climatic variables for thermal design of buildings in Dhahran. *Arabian Journal for Science and Engineering* 7 (2): 101-110.

Fang, J.B., and R.A. Grot. 1985. In situ measurement of the thermal resistance of building envelopes of office buildings. *ASHRAE Transactions* 91 (1B): 543-557.

Flanders, S.N. 1985a. Confidence in heat flux transducer measurements of buildings. *ASHRAE Transactions* 91 (1B): 515-531.

Flanders, S.N. 1985b. Heat flow sensors on walls—What can we learn? *Building applications of heat flux transducers*, pp. 140-159. E. Bales, M. Bomberg, and G. Courville, eds. Philadelphia: American Society for Testing and Materials.

Grot, R., et al. 1985. Instrumentation for the in situ measurement of building envelopes. *ASHRAE Transactions* 91 (2B): 1088-1100.

Hedlin, C.P. 1985. Calculation of thermal conductance based on heat flow rates in a flat roof using heat flux transducers. *Building applications of heat flux transducers*, pp. 184-202. E. Bales, M. Bomberg, and G. Courville, eds. Philadelphia: American Society for Testing and Materials.

Kuehn, T.N. 1982. Field heat-transfer measurements and life cycle cost analysis of four wood-frame wall constructions. *ASHRAE Transactions* 88 (1): 651-666.

Shu, L.S., A.E. Fiorato, and J.W. Howanski. 1981. Heat transmission coefficients of concrete block walls with core insulation. *Thermal performance of the exterior envelopes of buildings II*, pp. 421-435. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.