THE PERFORMANCE OF LIGHTWEIGHT INVERTED FLAT ROOFS

J. C. BEECH and G. K. SAUNDERS

Building Research Establishment, Princes Risborough Laboratory
Buckinghamshire, United Kingdom

ABSTRACT

The inverted, or protected membrane, flat roof has been a successful solution to problems of flat roof design when employed with heavyweight decks of high thermal capacity. However, when used with lightweight decks, such as metal or timber, there is concern that flow of rain water between the membrane and the overlaying insulant may seriously reduce thermal performance. This paper describes research carried out at Princes Risborough Laboratory (PRL) to assess this, using a specially constructed lightweight roof in service and a laboratory test rig. Heat flows and temperature profiles through the roofs were measured to determine the effects of water flowing over the roofs.

It was found that heavy prolonged precipitation and low external temperatures significantly distorted steady-state temperature profiles through the roof. Greatly increased heat losses resulted from the flow of water over the membrane. Because of the low thermal capacity of these roofs, transient heat losses could result in a marked reduction in the under-deck temperature, and a risk of condensation when high humidities were maintained in the room below. Local heat flows through the roofs were found to depend on factors such as the pattern of water flow over the membrane surface and gaps in the insulant layer.

The inverted roof, sometimes described as the protected-membrane roof, is a form of the warm-deck flat roof[1] design. The weatherproof membrane is laid directly on the structural deck and is covered by loose-laid slabs of rigid foam plastic insulant that resists moisture and weathering. Extruded polystyrene is widely used as insulant, since, in addition to its advantageous thermal properties, the material absorbs only a small proportion of its own weight of water when exposed for long periods to moisture. It is not damaged by repeated freeze-thaw cycles under these conditions.

Most types of insulant must be weighted, either with paving slabs or with a 50mm layer of stones, to prevent displacement by wind suction or by flotation in heavy rainfall.

The inverted roof has several advantages over the "sandwich" type of warm-deck flat roof. The waterproof membrane is protected against the weather, particularly the temperature extremes to which a membrane laid over an insulant is exposed. Because the membrane is not usually physically bonded to the insulant, it is not subjected to fatigue stresses caused by cyclic movements of the insulant in response to temperature change. However, because the insulant is generally loose-laid over the membrane, rain or melted snow is able to penetrate through its joints and flow over the membrane before it drains away at gutters. Depending on the way the insulant joints are formed, they may represent effective cold bridges for heat loss through the roof.

CURRENT KNOWLEDGE OF INVERTED ROOFS

The inverted roof concept has been described in the literature[2,3] and has won acceptance in the United Kingdom and particularly in Canada, the Federal Republic of Germany and Scandinavia as an acceptable solution to the problems posed by flat roof design and maintenance. Monitoring of such roofs over long periods[4,5,6] has demonstrated the advantages of the inverted construction over conventional warm-deck flat roofs. Detailed studies have been carried out on inverted roofs in service in which temperature profiles and heat flows through the roofs have been measured.[7,8] These have confirmed the technical feasibility of the inverted roof concept, both for new buildings, and for remedial work on existing defective flat roofs.

It should be noted, however, that all the studies to which reference has been made concern inverted roofs constructed over heavyweight concrete structural decks, which have significantly greater thermal mass than lightweight decks of timber or metal. For example, a 120mm-thick structural deck of dense concrete has thermal mass (inertia) approximately five times that of a lightweight deck of 25mm plywood over corrugated steel sheet.

Kunzel[7] and Petersson[8] demonstrated that temperature profiles through an inverted roof over a heavy concrete deck changed as a result of heavy rainfall during periods when the outside air temperature was low. The additional heat loss was shown to depend on the intensity of the rainfall, the temperature of the rainwater and the thermal resistance of the substructure including the deck. However, the temperature change at the underside of the deck was only slight, because of the large thermal inertia of the heavy concrete decks in both studies.

It was concluded that these additional routes for heat loss, which are characteristic of the inverted flat roof, do not constitute a risk of transient condensation occurring within the building below. Because such heat losses only occur when heavy rain flows over the roof and external temperatures are low, they can be accounted for simply by increasing the thickness of the insulant. A 20 percent increase in thickness is generally sufficient for this purpose.

Because of the low thermal inertia of a lightweight deck, such heat losses could result in a very rapid drop in temperature at the underside of the deck, with a risk of condensation occurring at some locations.

THE NEED FOR RESEARCH

Generally favourable experience with inverted flat roofs over heavyweight decks over a period of years, particularly in Germany, Scandinavia and Canada, has tended to confirm the findings of the studies described earlier. However, doubts have been expressed about the suitability of this design for roofs with lightweight decks.[9] Lightweight inverted roofs may be used in the future to upgrade existing lightweight decks of other designs for new projects, although relatively few exist at present. No studies were known in which the performance of inverted roofs of lightweight construction had been systematically monitored, so it was decided to undertake a programme at PRL that would include measurements on roofs in service, complemented by studies under controlled conditions in a specially constructed laboratory rig. One roof identified as a possible candidate for monitoring, a lightweight aluminum deck over a leisure centre in Ayr, Scotland, had already developed problems associated with water entry into the building. Unfortunately the roof could not be examined to determine the cause, and could not be used to obtain experimental data. However, this was a further indication of the need for more information on this type of roof.

EXPERIMENTAL ROOF IN SCOTLAND

Experimental data are presented for a lightweight experimental roof, constructed to BRE's specification. It consisted of a small, 5m by 2.5m precast concrete garage over which a lightweight deck of 18mm plywood over corrugated steel was constructed. The waterproof membrane was a 1.2mm-thick, single layer of PVC plastic sheet; 50mm-thick extruded polystyrene slabs of 32-35 kg/m^{3} density, 600mm wide and 1250mm long with rebated edges, were laid over this. A felt dust barrier was laid between the insulant and the 50mm ballasting layer of stones. The roof was built with a slope of 1 to 40, and the interior of the building was controlled at 18 ±2C and 95 ±5 percent relative humidity. The inside walls of the garage were lined with 50mm-thick polyurethane panels.

Figure 1 shows a plan view of the roof indicating the location of the joints between the individual polystyrene slabs, together with the positions at which thermocouples were placed within the roof. Figure 2 shows a section through the roof. Most temperatures were measured using copper/ constantan thermocouples and recorded on a 30-channel data logger. Other temperatures were measured using thermistors in conjunction with a pen-chart recorder. For some later tests the temperature of the water draining from the roof was also recorded by thermocouples placed at the outlet from the roof. Rainfall data were obtained using 8-inch recording rain gauges, and the amount of precipitation during 15-minute intervals was measured.

LABORATORY TESTS

Complementary studies were carried out using a small test rig which replicated the lightweight experimental inverted roof described above but which omitted the sheet steel deck.

The roof was 2400mm by 1200mm and was built above a 750mm-high insulated box to simulate a building interior. Within this box, conditions of temperature and humidity could be controlled, usually close to 18C and 95 percent relative humidity. The whole rig was enclosed within another, well-insulated 3.8m by 2.5m by 2.5m box in which temperature could be controlled to 0C using a climate generator. This simulated external conditions.

Instrumentation was similar to that of the experimental roof. Thermocouples were placed at five locations (Figure 3) to measure temperature profiles. At one location, number 4, two heat flow meters were installed, one within the insulant, the other inset into the plywood deck.

The outputs from the copper/constantan thermocouples and heat flow meters were recorded by a data logger. Rainfall was simulated by an array of plastic tubes with holes on approximately 40mm centres located 75mm above the surface of the rig on a wooden frame. The array was fed with water from a 300-litre tank, which could discharge the equivalent of a 1mm-per-minute rainfall over a period of two hours. According to Lacey[10] rainfall of this intensity may be expected in the United Kingdom for three-minute durations at least once a year.

Steady state conditions were established at 20C and 95 percent relative humidity inside and the temperature above the roof at 2C; 300 litres of water at 2C were then sprayed over the roof at approximately 2.5 litres per minute, the equivalent of a very heavy, 1mm-per-minute rainfall, and the effects on the roof monitored. Data was collected for some time after the flow of water ceased. A series of three tests was carried out with the heat supply beneath the roof varied within each test. Heat inputs were 2.5, 5.0 and 7.5kW.

A second series of tests was carried out after the insulant slabs had been repositioned, so that a second heat flow sensor could be embedded at the centre of a slab and placed directly above the heat flow sensor in the deck (position 4, Figure 3). A third series of tests was then performed in which the position of the heat flow sensors corresponded to a point midway between the centre and one edge of the central insulation board (position 2, Figure 3).

The final series of laboratory tests was performed after restoring the insulation boards to the configuration shown in Figure 3. However, the interlocking rebates were removed to form open butt joints about 3mm wide. Only the heat flow sensor in the deck was used in this test.

A different series of tests assessed the thermal performance, and particularly the condensation risk, when the heat supply below the roof was removed and the interior temperature allowed to fall. These tests were carried out with and without simulated rainfall.

At the conclusion of the tests the assembly was dismantled carefully and inspected to determine evidence of condensation below the waterproof membrane.

RESULTS: EXPERIMENTAL ROOF

From the measured temperature profiles at the nine locations that were instrumented, it was possible to compute local heat flows through the deck and the insulant layer respectively. With stable weather conditions, the thermal performance of the roof approached a steady-state condition. However, the periodic cycling of the heat source within the building by the thermostat caused heat flow through the deck to assume a "saw tooth" variation, with a mean value approximately equal to the steady value of the computed heat flow through the insulant. Locations 1, 2, 3 and 7 in Figure 4 show typical data.

Data for 11 periods, varying in duration from about five to 36 hours and during which measurable rainfall was recorded, were analyzed in detail. Table 1 gives selected data for the computed mean heat flows through the deck and through the insulant for the nine locations on the roof shown in Figure 1. Data for periods A and B are shown graphically in Figures 4 and 5.

In addition, Table 1 gives data from an experiment in which rainfall was simulated by spraying water over the roof.

The data shown graphically in Figures 4 and 5 demonstrate that true steady state thermal conditions are rarely achieved in periods during rainfall or immediately afterward while water is still flowing over the membrane. At such times, the flow of rain water affects the local heat flow through the roof at some locations. The contribution of this effect to the total heat flow was estimated by comparing the computed heat flows through the insulant and deck respectively. To minimize the error introduced by assuming steady state conditions, these heat flows were estimated as time-averaged values over the appropriate time spans during which rainfall was recorded:

$$\overline{q_d} = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} q_d(t).dt \qquad \overline{q_i} = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} q_i(t).dt$$

where q_d and q_i are the computed heat flows through the deck and insulant respectively and $t_2 - t_1$ is the time span during which rainfall was recorded.

The values for $\overline{q_d}$ and $\overline{q_i}$ were obtained by computer summation of the areas below the heat flow/time curves for periods of rainfall, and these values are given in Table 1.

Table 2 gives the computed time-mean values of the heat flow through deck and insulant, averaged for the periods of rainfall for each of the nine locations. The estimated local heat losses to rain flow are also shown as a proportion of the "normal" heat flow rate through the insulant only.

It should be noted that between the monitored periods on March 1 and 2 and on May 2 the stones and insulant panels were removed to allow access to the roof for repositioning the heat flow meters. This appears to have caused a change in the typical patterns of water flow between the membrane and the insulant panels, and, hence, in heat flows through the roof, particularly at locations 1, 2 and 3 where the membrane was disturbed to give access to the plywood deck. Mean value of heat flow in period A was 7.6 W/m² for both deck and insulant at positions 1, 2, 3. During period B, after disruption of the membrane, mean heat flow rates were 4.7 W/m² for the insulant and 26.7 W/m² for the deck.

The overall mean value of heat flow through the insulant, approximately 6.0 W/m² *(Table 2)*, is slightly lower than the 7.5 W/m² heat flow rate which would be expected to occur through the roof on the basis of its calculated thermal resistance based on the sum of thermal resistances of the individual layers and for the temperature differences recorded across the roof during the periods monitored. It will be noted that heat flow through the deck at location 7, the centre of an insulant board, is also of this order. In general, heat flow through the deck at other locations is significantly higher than through the insulant, and the difference, which represents the heat loss at the particular location to the rain water, is greater at joints in the insulant. This suggests that

flow of rain in discrete channels over the membrane is principally responsible for the observed local increases in heat loss from the deck. It seems probable that over the major part of the roof area remote from insulant joints, the rate of heat flow through the deck is similar to the heat flow through the insulant immediately above it, and is largely unaffected by water flow over the roof during and immediately after rainfall.

The computed local values of heat flow upwards through the insulant are likely to be less than the true rates, because the thermocouples placed at the bottom of the insulant are affected by the proximity of cold water at the membrane-insulant interface. This reduces the apparent temperature gradient through the insulation layer. The fact that the "steady-state" temperature at this interface is suddenly reduced when cold water percolates down through the insulant joints results in a real reduction in the flow upward through the insulation. However, the heat loss from the bottom of the insulant to the water is very slight compared with that from the deck because of the very low thermal conductivity of the insulant.

The computed heat flows through the deck and insulant at specific locations do not enable us to estimate the contribution of the additional heat loss because of rainfall to the overall heat loss through the inverted roof. An estimate of these losses may be obtained from the measured total temperature difference across the roof, from a heat balance calculated from the measured rainfall rates in each quarter-hour period and the temperature increases observed as water flowed over the roof.

These data were obtained over three periods totaling 21 hours duration, and the total calculated heat gain represented a mean rate of heat flow to the water of 23 watts. The theoretical heat loss rate through the roof, calculated from the overall thermal resistance (2.0m² deg C/W) and the mena temperature difference ($\triangle T = 15C$) between the internal and external air during the period of monitoring was 88.5 watts.

We may therefore express the total heat loss as:

$$Q = Q_c + Q_r \text{ (watts)}$$

where: Q_c = heat loss by conduction through roof

Q_r = heat loss to water during or following rainfall; and the effective thermal transmittance ($U = 1/R$) of the roof during rainfall periods as:

$$U = \frac{(Q_c + Q_r)}{A.\triangle T} = 0.50 + 0.13 \text{ (m}^2 \text{ deg C/W)}$$

where: A = total roof area.

Expressed as heat flow rates during these periods of rainfall these values become:

$$q = q_c + q_r \qquad = 7.5 + 2.0 \qquad = 9.5 W/m^2$$

Under varying conditions of rainfall, between 0.2 and 4.2mm/hour in any 15-minute period during the total 21 hours considered, the thermal transmittance attributable to heat loss to rainfall (U_r) amounted to about 20 percent of the total heat loss from the roof. This may be contrasted with the data in Table 2 which suggest that at joints in the insulant the local heat loss to rain water at the membrane may be as much as six times the typical value for heat flow through the roof when heat transmission is unaffected by rainfall.

LABORATORY TESTS RESULTS

The experimental data include both directly measured heat flow rates and temperature gradients measured through the deck and the insulant, respectively, during periods of normal heat transmission, and during periods of very heavy simulated rainfall. It is thus possible to estimate the effective thermal resistance of the roof assembly over chosen periods from integrated values of the measured heat flow rate, and the temperature difference across the roof, both as functions of time. Since under steady-state conditions the thermal resistance of the roof is $R = \triangle T/q$, we may calculate the effective value of R during any time period in which both $\triangle T$ and q vary with time, as:

$$\overline{R} = \int_{t_1}^{t_2} \triangle T(t)dt \, / \int_{t_1}^{t_2} q_d(t)dt$$

where: $\triangle T(t)$ is the difference between inside air and external air temperatures at time t; and $q_d(t)$ is the measured heat flow rate through the deck at time t. The theoretical value of R, computed from the thermal transmittance values of the constituent layers is 1.86 m^2 deg C/W *(Table 3)*. Any effects of water flow over the membrane will be reflected in a reduction of R as a consequence of the increase in the measured mean heat flow rate.

The data from the tests carried out on the test rig are summarized as $\overline{R}$ values in Table 3. They include the mean value of the thermal resistance $\overline{R}$ calculated from 22 periods, each of 24 hours duration, during which the apparatus was allowed to attain quasi steady-state conditions without simulated rainfall. The mean value of $\overline{R}$ from these tests, 1.77 m^2 degrees C/W with standard deviation of 0.26, may be compared with the values of $\overline{R}$ obtained by integrating the $\triangle T(t)$ and $q_d(t)$ curves for various tests with rainfall, and different configurations and positions of the insulant joints in relation to the heat flow sensor embedded in the plywood deck. The value of $\overline{R}$ for positions at the centre of an insulant board, 1.88, and midway between the centre and the edge of a board, 1.42 are not markedly different from the mean value without water flow.

In contrast, the local thermal resistance at a joint in the insulation boards is significantly reduced to about 20 percent of the normal value. However, the values of R for the interlocked boards and for open butt joints show no significant difference. It may be concluded that the amount of water passing through the joints is similar in either case. It must be noted that the volume of water flow in these tests, equivalent to approximately 1.0mm per minute, is extremely high compared with the highest rainfall rates which were measured in service, approximately 4mm per hour in any quarter-hour period. The influence of simulated rainfall in reducing the effective thermal resistance of the roof was found to extend for periods of several hours after water flow was stopped.

Heat flow rates measured directly by sensors embedded in the deck and in the insulant were found to agree well under steady-state conditions without water flow. The directly measured heat flow rates were generally found to be equal, within experimental error, to computed values. Steady-state heat flows without water flow over the roof were in fair agreement with values calculated from the total thermal transmittance, 0.54 W/m^2 deg C, of the roof assembly. Table 4 gives data for the five locations *(Figure 2)*. Internal temperature was controlled at 20C using a thermostated 2.5kW heat supply. External temperature was controlled at 2C. Joints between insulant slabs were interlocked.

Note the very large increase in local heat flux at the joints in the insulant (locations 1, 3, 4 and 5, *Figure 3*), with water flow. This phenomenon is less marked at location 2, at the centre of a board. Here the heat flow rate returns more rapidly to the normal value once water flow stops.

As with the tests on the roof in service, these measured values of heat flow through the roof at different locations do not enable us to deduce the overall contribution of heat loss because of water flow to the heat loss rate for the whole roof assembly. An experiment to measure the temperature increase of the water and its flow rate over the roof yielded an average calculated value of heat flow to the water of 47 W/m^2 for the total roof area. In each case, the temperature rise of the water was measured at five-minute intervals during the last 40 minutes of a two-hour test, when it was apparent that the two water temperatures were relatively stable.

HEAT LOSS AND RAINFALL RATES

Let us compare the mean heat flow rate of 47 W/m^2 calculated for the whole laboratory roof assembly with simulated rainfall with similar data for the experimental roof. With considerably smaller rain flows, the latter amounted to 2 W/m^2 over the whole roof area during a period of 21 hours with variable rainfall. The maximum rate was 4mm per hour, and the mean 1.6mm per hour.

The transfer of heat by forced convection from a surface to water in turbulent flow may be represented as:

$$Q = K. \frac{V^{0.8}}{d^{0.2}}$$

where V is the velocity of flow and d is a linear dimension characteristic of the flow channel.

The relative heat and mass flow rates conform fairly well to the relationship: $Q_r \sim$ (rain flow rate).$^{0.8}$ It may be reasonably assumed that any deviation is due mainly to differences between the water flow patterns on the two roofs. Tests on the experimental roof suggested that local heat flow rates depend on whether the flow of water tends to be directed to the particular location by topographic factors, such as undulations or ridging of the membrane surface, or variations in the gap between membrane and insulant.

Attempts to correlate the calculated enhancement of the local heat flows with rain intensity on the experimental roof were only partially successful. At locations where rainfall produced a marked increase in heat flow through the deck, (locations 4, 6, 8 and 9; *Figures 4 and 5*) some correlation was achieved only by considering short time spans during which heavy rain was observed. However, the relationships found between heat lost to water and rain intensity were different from that deduced from earlier estimates. It is evidently not possible to generalize from the locally measured data.

Another factor is the continued high rate of heat loss through the deck after rainfall ceases. This is probably due to the absorption of sensible heat from the deck by water trapped between the membrane and the insulant. Latent heat of evaporation of a small proportion of this water may also contribute.

CONDENSATION RISKS

No evidence of condensation was found in the experimental roof in Scotland as high internal temperatures were maintained. Water problems inside the leisure centre in Scotland may have been due to condensation occurring when the internal temperature fell overnight.

Tests with the laboratory rig examined the effects of heat losses due to water flow when the internal temperature was allowed to fall. As would be expected, the rate at which internal temperature decreased was considerably greater with flow of water over the roof (to 7C within two hours) than without (to 13C). After this test had been completed, the rig was dismantled to examine the plywood deck. A considerable quantity of water was present on the top surface of the plywood. Because the membrane was intact it was concluded that this was caused by the condensation of internal moisture vapour immediately below the membrane.

CONCLUSIONS

1. Lightweight inverted flat roofs designed to have similar total thermal transmittance to those with heavyweight decks will perform similarly in the absence of heavy precipitation.

2. The low thermal mass of the lightweight deck makes these roofs vulnerable under conditions of heavy rainfall (and probably with rapid melting of heavy snow) and low external air temperatures.

3. Local heat losses to rain flowing through joints in the insulant layer and over the waterproof membrane were greatly increased at the joints. The water effectively forms cold bridges in the insulant.

4. There is an increased risk of condensation at the under-surface of the roof deck at such locations, particularly when intermittent heating of the building allows internal temperatures to fall for several hours. Any condensation risk may be effectively reduced by placing additional insulation below the membrane.

5. During periods of moderate rainfall, heat loss from the roof because of the removal of heat at the membrane-insulant interface by water flowing over, or trapped on, the roof was estimated to be 20 percent of the normal transmission. This proportion is likely to increase markedly in periods of heavy rainfall.

Local heat flow rates (W/m²)		Locations on roof								
		1	2	3	4	5	6	7	8	9
Through deck	$\overline{q_d}$	13.4	13.0	17.8	33.8	19.1	35.3	13.1	43.3	35.9
Through insulant	$\overline{q_i}$	7.2	6.6	6.2	4.1	6.8	4.9	6.8	5.0	5.4
To rainfall	$\overline{q_d} - \overline{q_i} = \overline{q_r}$	6.2	6.4	11.6	29.7	12.3	30.4	6.3	38.3	30.5
q_r as fraction of "normal" heat flow	$\overline{q_r}/\overline{q_i}$	1.05	1.08	1.97	5.03	2.08	5.15	1.06	6.49	5.17

Mean value of $\overline{q_i}$ for all 9 positions = 5.9 W/m²

Table 2 Experimental roof. Computed time-averaged heat flow rates. Mean values for all periods with rainfall.

Conditions of test		$\overline{R} = \dfrac{\overline{\triangle T}}{q_d}$ (m² deg C/W)	
Water flow	**Location**	**Test values**	**Mean values**
None	At joint in insulation (location 4)	(SD of 22 periods of 24 hours = 0.26)	1.77
With simulated rainfall of 1 mm/min	At open interlocked joint (location 4)	0.30 0.32 0.36	0.33
	At open butt joint	0.28 0.33 0.30	0.30
	At centre of insulant slab	1.46 2.10 2.07	1.88
	Halfway between centre and edge of slab	1.41 1.47 1.38	1.42

Theoretical thermal resistance, R, is the sum of the resistances of the layers of the inverted roof:

inside air	0.12 m² deg C/W
plywood	0.09 m² deg C/W
insulant	1.50 m² deg C/W
stones	0.10 m² deg C/W
outside air	0.05 m² deg C/W
Total R =	1.86 m² deg C/W

Table 3 PRL Laboratory rig. Measured values of effective thermal resistance (R) of roof showing the effect of simulated rainfall.

Date & duration of period of rainfall	Temp below stones (C)*	Air temp (C)	Rain index (mm/h)	Time-averaged heat flows W/m²) (a) through deck (b) through insulant at locations:								
				1	2	3	4	5	6	7	8	9
PERIOD A (Fig 4) 1 & 2 March 17.00 to 10.00	5.9	5.4	0.7	(a) 10	7	6	22	22	30	9	43	34
				(b) 8	7	8	5	8	6	8	5	6
PERIOD B (Fig 5) 2 May 09.16 to 19.01	6.5	3.8	3.1	(a) 15	22	43	39	17	37	16	41	36
				(b) 6	5	3	3	6	3	6	4	4
Simulated rain test: 23 March 12.00 to 14.00	11.6	—	—	(a) 17	27	14	25	34	31	4	18	26
				(b) 3	1	3	2	2	4	4	3	1

*Mean value for three locations (3, 6, 9)

Table 1 Experimental roof. Selected data for mean heat flow rates through deck and insulant with rainfall.

| Conditions	Mean heat flow rates (W/m²) through deck calculated for locations					
	1	2	3	4	4 measured directly	5
Steady-state before water spray	13	11	20	17	12	14
During water spray (steady condition)	115	38	57	67	58	113
During 1st hour after water	62	17	49	43	43	76
During 2nd hour after water	38	20	39	25	25	57

Table 4

GLOSSARY OF SYMBOLS

Symbol	Definition	Units
A	Area of roof	m²
Q	Heat loss from roof	W
Q_c	Heat loss by conduction	W
Q_r	Heat loss to water during or following rainfall	W
q	Heat flow rate	W/m²
q_c	Heat flow rate due to conduction	W/m²
q_r	Heat flow rate to water on roof	W/m²
q_i	Computed heat flow rate through insulant	W/m²
q_d	Computed heat flow rate through deck	W/m²
$\overline{q_i}$	Time-averaged heat flow rate through insulant	W/m²
$\overline{q_d}$	Time-averaged heat flow rate through deck	W/m²
$\overline{q_r}$	Computed heat loss to rainfall	W/m²
R	Thermal resistance of roof	m² deg C/W
$\overline{R}$	Thermal resistance computed from $\overline{q_d}$ and $\overline{\Delta T}$	
t	Time	hours
T	Temperature	C
ΔT	Temperature difference	deg C
$\overline{\Delta T}$	Time-averaged temperature difference	deg C
U	Thermal transmittance of roof	W/m² deg C
U_r	Thermal transmittance attributable to rainfall on roof	W/m² deg C

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South (high) end
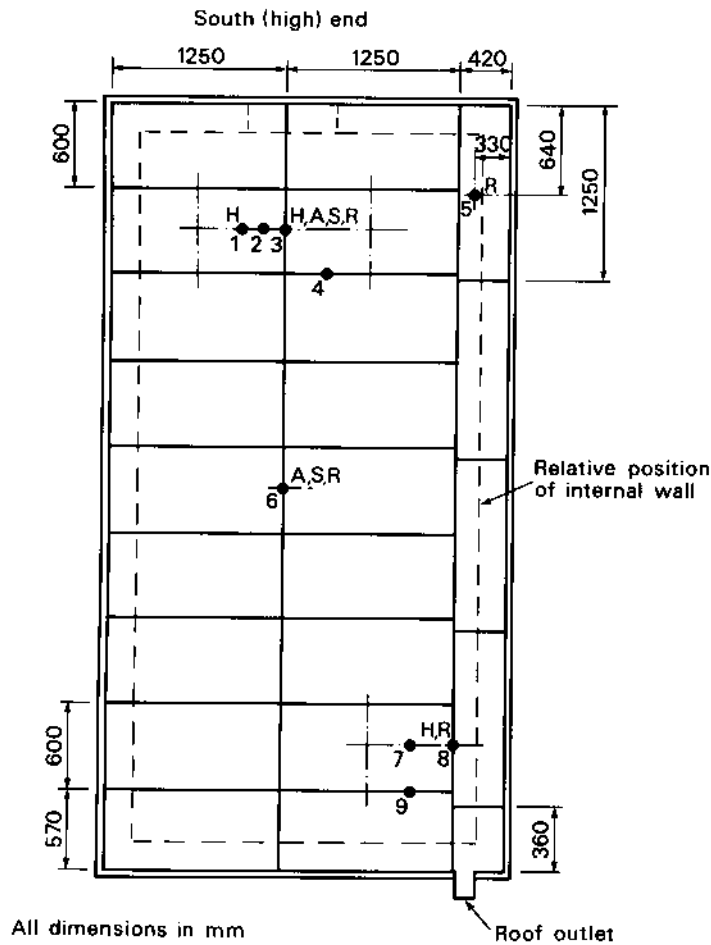
All dimensions in mm

Instrumented with thermocouples at locations 1-9

Additional sensors (as indicated)

A : external air temperature

R : internal air temperature

S : surface temperature of stones

H : heat flow
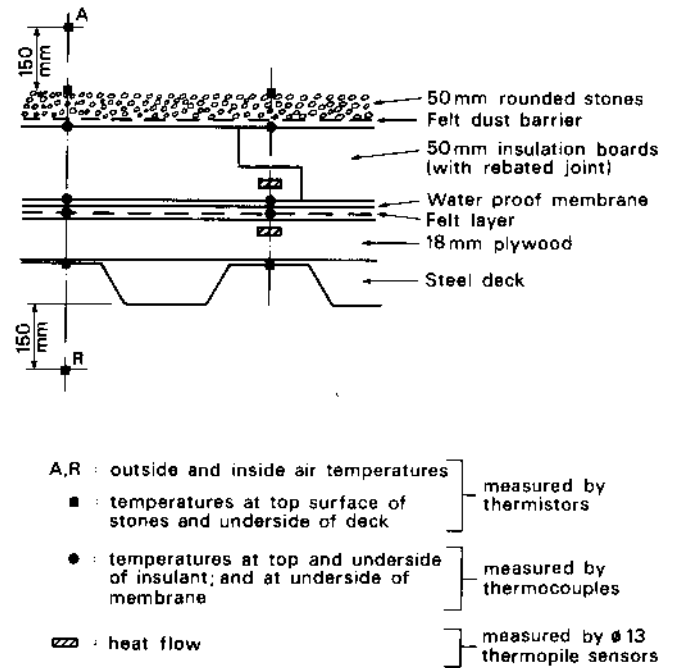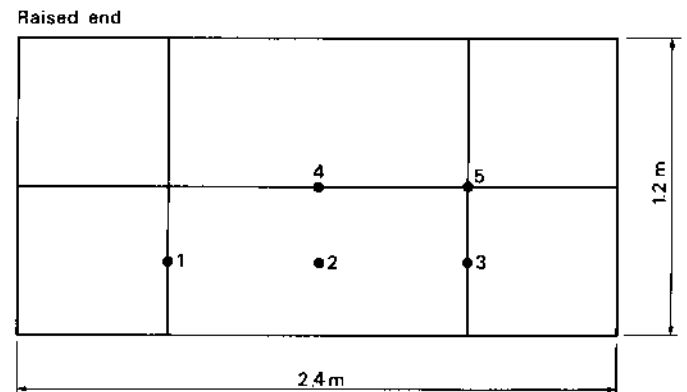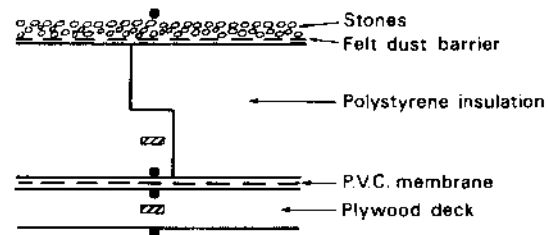
Figure 1   Plan of experimental roof

- 50mm rounded stones
- Felt dust barrier
- 50mm insulation boards (with rebated joint)
- Water proof membrane
- Felt layer
- 18mm plywood
- Steel deck

A,R : outside and inside air temperatures — measured by thermistors

■ : temperatures at top surface of stones and underside of deck — measured by thermistors

● : temperatures at top and underside of insulant; and at underside of membrane — measured by thermocouples

▨ : heat flow — measured by ∅13 thermopile sensors

Figure 2   Section through experimental roof

Raised end

a) Configuration of insulation boards and position of monitoring points

- Stones
- Felt dust barrier
- Polystyrene insulation
- P.V.C. membrane
- Plywood deck

b) Section showing positions of heat flow meters & thermocouples

● : thermocouple

▨ : heat flow meter

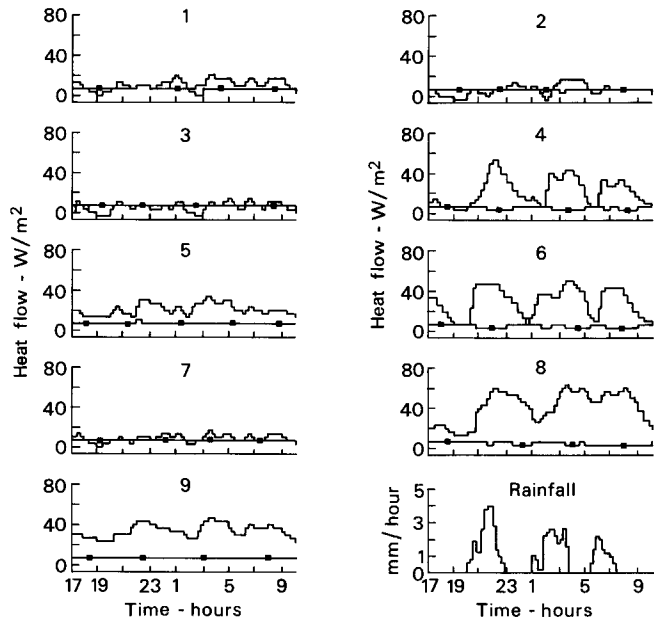*Figure 3   Laboratory test rig—roof construction*

Figure 4 *Experimental roof. Computed heat flow rates (locations 1-9) and rainfall for period A.*
solid line = heat flow rate through deck
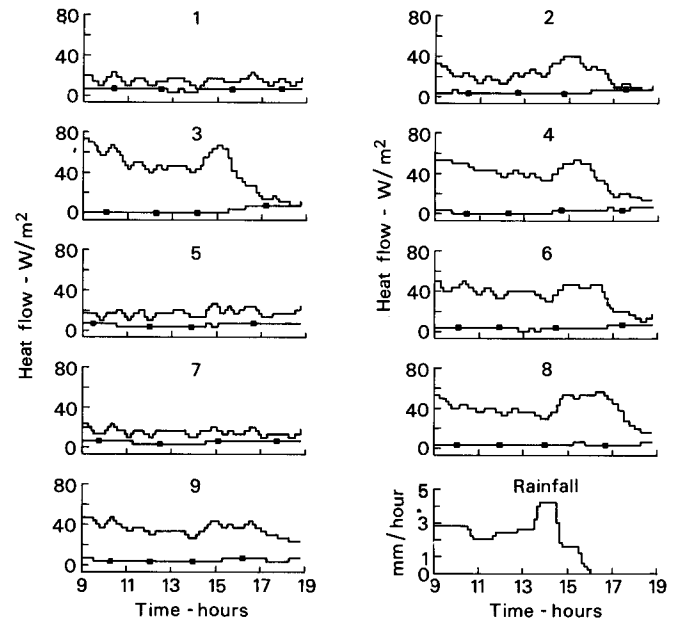*dotted line = heat flow rate through insulant*

Figure 5 *Experimental roof. Computed heat flow rates (locations 1-9) and rainfall data for period B.*
solid line = heat flow rate through deck
dotted line = heat flow rate through insulant