A STUDY OF THERMAL PERFORMANCE OF OPERABLE ROOF INSULATION, WITH SPECIAL REFERENCE TO DHAKA

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To

my son Reshad ,daughter Kinjal
and their loving mother Luna

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

The roof is the main element of a building that has much exposure to the sky and therefore it is the most appropriate location for a nocturnal radiator. High mass roof with operable insulation of concrete provides the functions of cold collection and of storage in one element. Roofs are usually insulated to minimize heat loss in winter and minimize heat gain in summer. As the radiant loss takes place at the external surface of the roof, the insulation minimizes the actual cooling that a building can utilize from the nocturnal radiation. If these roofs could be equipped with operable insulation that cover the roof during the day and expose to sky during the night, the roofs would function as effective nocturnal radiators and cold storage elements. Therefore this type of radiant cooling using operable insulation is effective in providing daytime cooling in almost any region, preferably with low cloudiness at night, regardless of low humidity.

The impact of solar radiation affects the thermal behavior of roof more than any other part of the structure especially in Tropical countries. In Bangladesh most of the buildings in urban area have flat concrete roof. This roofs as exposed to direct solar radiation elevates indoor temperature usually above the local comfort level in summer. Active means of cooling is generally very expensive and in high ambient temperatures usefulness of ceiling fan is greatly reduced, particularly on top floor of the buildings. Thus, the thesis investigates the potential of using Operable Roof Insulation over concrete roofs as an alternative method of passive cooling by studying the thermal performance and its influence on energy use in the context of Dhaka during hot months of the year.

The problem was approached first by a survey of published information that provided the knowledge base for the research and inform about the state of the art with regard to passive cooling systems followed by Problem Modeling, which was a combination of Simulation study and Field study. The studies were conducted during the month of April, May and June of 2002 representing hot-dry and hot-wet period; which are obviously most significant in terms of climatic severity.

The simulation studies were performed to appraise the effects of insulation and other parameters over time and to investigate aspects, which could not have been derived from the field studies. In the course of field work, a test room was selected at the top floor of a four storied building to establish a base case on which the proposed roof system was applied and performance evaluated in relation to local comfort temperature range. The study involved simultaneous recording of environmental data, such as air temperature, radiant temperature, humidity, ceiling temperature and rooftop temperature for two situations, first without operable roof insulation system and then with insulation by programmable real time 'Data Loggers'.

The significant findings of the thesis are concerned with the effect of operable roof insulation in the test room in terms of indoor comfort by nocturnal radiative cooling and thermal performance of operable roof insulation. Results indicate that there is a considerable potential for nocturnal cooling and the thermal performance of operable roof insulation significant with respect to uninsulated test room condition. Simulation studies and the Fieldwork jointly provide the basis for design guidelines for operable roof insulation. It is expected that these guidelines will reduce effect of solar radiation and promote radiative cooling option to create a comfortable indoor space.

CHAPTER ONE

GENERAL BACKGROUND

1.1 INTRODUCTION

The roof is the building component most exposed to the climatic elements. The impact of solar radiation particularly on clear days, the loss of heat by long wave radiation during the night, all affect the thermal behavior of roof more than any other part of the structure. Under warm ambient conditions in the tropics, the indoor air temperature is affected by the roof, to an extent dependent on certain details of thickness, density, type, color etc. In hot countries, it is popularly believed that the roof is the main heating element of a home. This is so in the majority of cases but only because the roof is incorrectly designed (Givoni, 1963).

Most of the buildings in the urban areas of Bangladesh (specially in Dhaka) usually have flat concrete roof and generally fixed insulation is applied over the roof. Throughout the day the roofs are exposed to direct solar radiation from the high summer sun elevating the indoor temperature often above the local comfort (Ahmed, 1995)(Mallick, 1994) level. Mechanical cooling is a very expensive option to counter this problem and the commonly used ceiling fans do little to improve comfort in high ambient temperatures. In such a context the need to develop passive means of solar control is important for comfortable living and higher productivity in hot seasons of the year.

Any ordinary surface that 'sees' the sky looses heat by the emission of long wave radiation towards the sky and can be regarded as a heat radiator. Although the radiant heat loss takes place day and night, the radiant balance is negative only during the night. During the daytime the absorbed solar radiation counteracts the cooling effect of the long wave emission and produces a net radiant gain.

The simplest concept of radiant cooling is that of a heavy and highly conductive roof exposed to sky during the night but highly insulated externally during daytime by means of operable insulation. Such roofs can be very effective in losing heat at night, both by long-wave radiation to the sky and by convection to the outdoor air, which cools down faster than the massive roof. During the daytime, the installed external insulation minimizes the heat gain from solar radiation and from the hotter ambient air. The cooled mass of the roof can then serve as a heat sink and absorb, through ceiling, the heat penetrating into and generated inside the buildings interior during daytime hours (Givoni 1998)(Goulding et al, 1992).

Therefore, the concrete roofs, which are very common in our context, with applied operable insulation, can provide effective radiant cooling and maintain the indoor temperature well below the outdoor level.

1.2 STATEMENT OF THE PROBLEM

Along with the high outdoor temperature, solar radiation is a major source of heat gain for buildings in Bangladesh. If we draw a general comparison between rural and urban houses in our context it will be evident that these rural houses consist of one storied (often single cell) units around a courtyard. They are based on low investment and high maintenance and the general construction materials mud, bamboo, thatch etc. These houses are extensively protected from effect of solar radiation by trees, which produce its own microclimate. In rural areas most of the activities are performed in outdoor and indoor comfort is mainly important during night time (Mallick, 1993). Moreover, the traditional built forms of the rural areas often include sound solution of climatic problems. Given technological limitations and the always-overriding considerations of safety, some of these solutions must be considered ingenious (Koenigsberger et al, 1973).

On the contrary, life is different in the cities, where a good number of activities take place in the indoor. Buildings are constructed with permanent materials, closely packed and often without the benefit of trees to provide protection. This problem is more intensifies in top floors of the buildings where roofs are exposed to direct solar radiation.

Modern construction in urban areas of Dhaka is characterized by extensive use of brick and concrete. High-rise buildings are being constructed to accommodate ever-increasing population. Although air flow is an important consideration but due to heavy concentration of the buildings this is not always successfully achieved and the concept of prevailing wind direction doesn't work in many instances. Mutual shading protects the wall of the buildings in closely placed buildings but roofs are exposed to direct solar radiation in association of sol-air- temperature[1] heat up the interior of the upper floor well

[1] For building design purpose it is useful to combine the heating effect of radiation incident on a building with the effect of warm air. This can be done by using the sol-air-temperature concept. A temperature value is found which would create the same thermal effect as the incident radiation in question, and is added to the air temperature 9koenigsberger et al, 1973): $T_s = T_o + (I{\times}a)/f_o$
where T_s = sol-air-temperature in °C, T_o = outside air temperature in °C, I= radiation intensity in w/m^2, a = absorbance of surface, fo = surface conductance (outside) in W/m^2 deg C

above the comfort level. Scope of shading provided by trees is limited and not beyond two story heights.

There are no standards for roof insulation in the building codes of Bangladesh but there are some practices. In many cases flat concrete roofs as cast are not graded properly for water runoff, therefore some roofs have a 75mm layer of lime terracing to grade it. This provides some degree of insulation but may deteriorate substantially after a number of years and its insulating property may reduce. Moreover, the cost of lime terracing is also going up and the process is time consuming (Mallick, 1993).

Some attempts have been made by roof gardening but no scientific data is available regarding its performance. There are one or two examples of double roof in Dhaka, although they are effective from thermal point of view but few can afford it as it involves substantial amount of money.

So, a system is required, which can be effective in 24-hour cycle. An operable Roof Insulation utilizing radiant cooling potential can be an answer.

1.3 APPROACH TO THE PROBLEM

Previously some attempts were made to improve roof insulation. A study by Imamuddin and others using hollow blocks plastered over concrete roof has found differences of about 4-5 °C between the ceiling surfaces of such an insulated slab as compared to a standard concrete slab for flat roofs. The difference was more for inclined roofs. The difference in room temperature was however less, a maximum of 2 °C (Imamuddin et al, 1993). But the study is incomplete, as it did not record temperature data for 24 hours.
Another study was conducted by F.H. Mallick by using earthen pot laid over concrete roof. The room temperature of insulated roof was found to be 2.5-3.4 °C lower in comparison with uninsulated roof at around 3 P.M. (Mallick, 1993).
It is evident from both experiment that using fixed insulation on the roof top, day time temperature can be reduced to a level but these methods reduce the potential of radiant cooling as in both cases the indoor temperature is higher than the outdoor.

Roofs are usually insulated to minimize heat gain in summer and heat loss in winter, but it minimizes the actual cooling potential that a building can utilize by the nocturnal radiation (Martin, 1989)(Clark, 1989). If these roofs could be equipped with operable insulation that cover the roof during the day to decrease the heat gain from solar radiation and from the hotter ambient air and during nighttime the insulation can be retracted to expose the roof slab to the night sky to lose heat both by long-wave radiation and by convection, the roof would function as an effective nocturnal radiator (Givoni, 1994). This thesis approaches the problem from this point of view.

1.3.1 Objective of The Research

The purpose of this study is to identify alternative means and devices of passive control compatible with the contemporary building technology and discover new methods and systems to make a building itself an energy modifying instrument towards a conceptually coherent approach for a low energy, environment friendly and sustainable architecture. The study aims to investigates the potential of using Operable Roof Insulation over concrete roofs as an alternative method of passive cooling specially in hot- dry and hot-wet season of the year with the following objectives:

- To study the potential role of Nocturnal Radiative Cooling technique in Dhaka.
- To evaluate the thermal performance of the Operable Roof Insulation in Dhaka.

1.3.2 Simulation Study

Simulation studies were conducted to evaluate the effect of insulation and other parameters over time and to investigate variations in parameters not covered by local comfort temperature range. Temperature data (ambient and radiant temperature) were collected for two situations, first without operable roof insulation system and then with insulation by programmable real time 'Data Loggers' installed inside the room and also at outside over a period of time. Based on the findings of the experimental study, further parametric studies were conducted by simulation to evaluate the effect of operable roof insulation on indoor air temperature, which were not covered by field study. The survey involved the simultaneous recording environmental data such as air temperature, radiant temperature, humidity, ceiling temperature, and rooftop temperature. The study focused on evaluating the performance of operable roof insulation in the test room in terms of indoor comfort. Such an understanding would enable to alter the characteristics of the physical environment to create comfortable indoor space.

The simulation studies and the fieldwork jointly provided the basis for design guidelines.

1.4 STRUCTURE OF THE THESIS

The second chapter presents the microclimate and the environmental factors of Dhaka. Seasonal characteristics of the climate are presented based on published information and published data. Impact of urbanization on microclimate is also discussed in this chapter.

The third chapter develops the theoretical background for the fieldwork on thermal comfort. Issues like definitions, factors influencing thermal comfort, relationship between insulation and comfort etc, are discussed.

The fourth chapter deals with the radiative cooling, the process which is utilized by the insulation system. In this chapter basic sky radiation is explained, different methods of radiative cooling process especially with operable roof insulation is discussed.

Fifth chapter illustrates the performance of roof insulation and its impact in the test room by simulation study. Here a detailed description of the software used for simulation is given. Furthermore detailed descriptions of the test room including material thermal properties are described. Discussion of results of insulation with various heights and their comparative study are also included in this chapter.

Sixth chapter demonstrates the performance of roof insulation and its influence in test room by field study. Objective and methodology of the fieldwork is discussed. Field results in three different conditions are also presented with comparative study among them. Chapter seven is the final chapter of the thesis. This chapter is based on the summary of findings drawn from previous chapters. Thermal performance of operable roof insulation based on simulation and field study are evaluated and discussed which provides the basis for recommendations. Based on this work suggestion for further research are also identified in the later section of this chapter. The overall outline of the research work is illustrated in Figure 1.1.

1.5 SCOPES AND LIMITATIONS

The main limitation (but also the opportunity of the research) is the lack of systematic studies in this particular field of knowledge with regards to Bangladesh. While a number of studies have been carried out in hot and dry regions exploring potentials of nocturnal cooling, little work in warm humid regions has been done.
Study on fixed insulation (specially lime terracing) is beyond the scope of the research as study on thermal performance and nocturnal cooling potential of operable roof insulation is the main theme of the research.

There are some other limitations in the research such as:

- Some degree of uncertainty may be present in the data collection during field investigation due to leakage of air flow between the roof and the insulating membrane as the whole installation was not airtight.
- In field investigation environmental data for the test room with different heights of operable roof insulation was not collected simultaneously. They were conducted in different months of the year. However thermal behavior of the test room was evaluated with respect to the ambient climate, therefore simultaneous data collection was not mandatory and had little bearing on the results.
- The effect of temperature drop between upper and lower skin of the insulating membrane was not measured in isolation due to the consideration of composite effect of the insulating membrane, air layer beneath and the reinforced concrete slab.

With these opportunities and constrains, research on thermal performance of operable roof insulation with special reference to Dhaka was carried out and described in the following chapters.

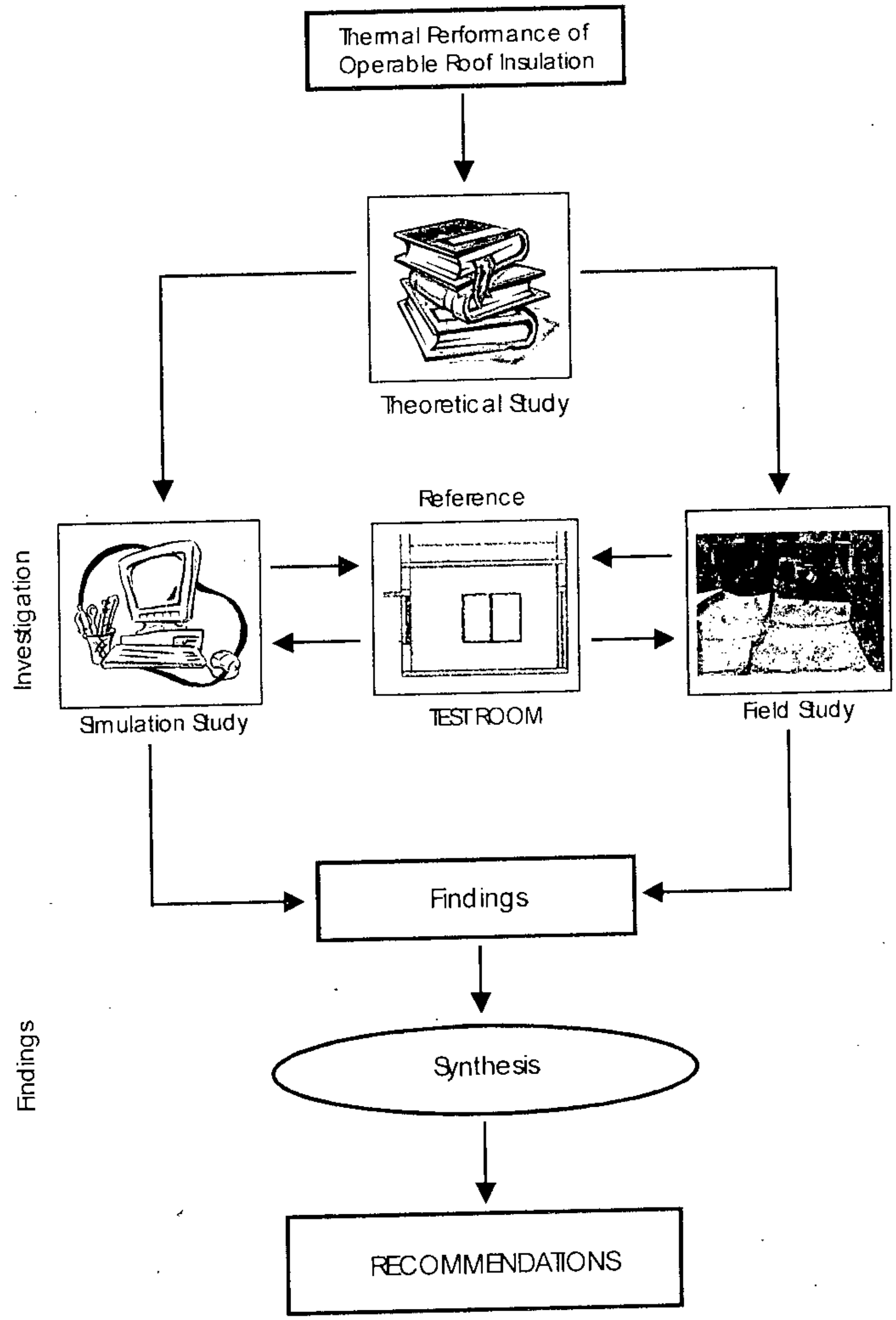

Figure 1.1 Structure of the Work

1.6 Reference

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CHAPTER TWO

THE CLIMATIC CONTEXT: DHAKA

2.1 INTRODUCTION

Now-a-days urbanization is taking place at an extremely rapid rate because of increasing population. This rapid urbanization sometimes may lead to severe problems associated with environmental deterioration, unhealthy living conditions, shortage of energy, water and increased exposure of the population to floods or extreme winds specially in the countries where natural calamities are recurring phenomena. If climatological information, principles and experiences were incorporated in the planning of rapidly growing urban areas, most of the above problems could be solved. (Karmakar and Khatun, 1993) Urbanization has impacts on urban climates (Oke, 1979) (Landsberg, 1981); rapidly growing buildings, industries, roads etc. in urban areas have effects on Radiative cooling/heating, precipitation, fogs, visibility, wind direction etc. The type of materials and design of buildings, the drainage system all depends very much on climatic elements and their extreme values.

The elements and components formulating the landscape of cities affect the regional climate through a complex interaction generating distinct microclimates. The changed climate due to the pressure of the city can be broadly termed as the microclimate of the city. The city with all its built form and anthropogenic activities having own mechanistic interpretation creates peculiarities within the climate substantially different from the regional climate (Ahmed, 1994). Proper environment evaluation at an urban scale can be made possible by appropriate appreciation of the environmental characteristics at a regional scale. Based on the human comfort issue, the following chapter analyses the climate of Dhaka in terms of its problems and potentials. Furthermore this study will help in identifying local environmental particulars having strong local deviations and at the same time those, which are congruent with that of the regional patterns. The designers and planners must consider the climatic factors and the extreme values of climatic elements before commencing any construction procedure.

2.2 MICROCLIMATE OF DHAKA CITY

The city of Dhaka lies between longitude 90°20' E and 90°30' E and between latitudes 23°40' N and 23°55' N at the southern extremity of the Pleistocene Terrace of the Madhupur Tract. The city is surrounded on three sides by rivers and low flood plains of these rivers. The river Buriganga, on which stands the Dhaka river port, flows along the south of the city. The river Balu and Turag are to the east and west respectively. A small channel known as Tongi khal connects Balu with Turag to the north of the city (Figure 2.1).

The climate of Dhaka is tropical and greatly influenced by the presence of Himalayan mountain range and Tibet plateau in the north and Bay of Bengal in the south. The climate is characterized by four main meteorological seasons, namely Winter (December to February), Pre-Monsoon (March to May), Monsoon (June to September) and Post-Monsoon (October to November). Seasonal characteristic of winter is cool-dry, pre-monsoon is hot-dry, while monsoon and post-monsoon is characterized by hot-wet environment.

Due to the physical development and location, the climate characteristics of one city differs from others and further modified in different locations within the city depending on difference in surface qualities, density, heights (three dimensional objects) and other related factors (Koenigsberger et al, 1973); as a result climate characteristics of Dhaka city differ from other cities of Bangladesh. This fact is more pronounced in developed nations where physical features of urban areas have more difference with surroundings, than tropical environments of developing countries (Jauregui, 1993). However, several investigations have been conducted to assess Dhaka's urban climate characteristics (Asaduzzaman, 1992) (Hossain and Nooruddin, 1993) (Ahmed, 1993). The following review of urban climatic factor is based on those investigations and on data from meteorological sources of the city (also see Appendix 5 for more detail).

2.2.1 Temperature

The temperature profile of Dhaka city based on meteorological data shows a clear congruity with the regional pattern and according to data accounts for 1950 to 1980 exhibits monthly maximum average temperatures recorded in March, April and May (pre-monsoon period) are relatively higher; reaching the highest at 34.5°C in April. During June to September (monsoon period) mean maximum temperature swings between 25°C to 26°C and average temperature remains steady at 28.6°C. In winter the temperature drops to an average of 18.6 °C while mean minimum is 11.7 °C recorded in January (Table2.1).

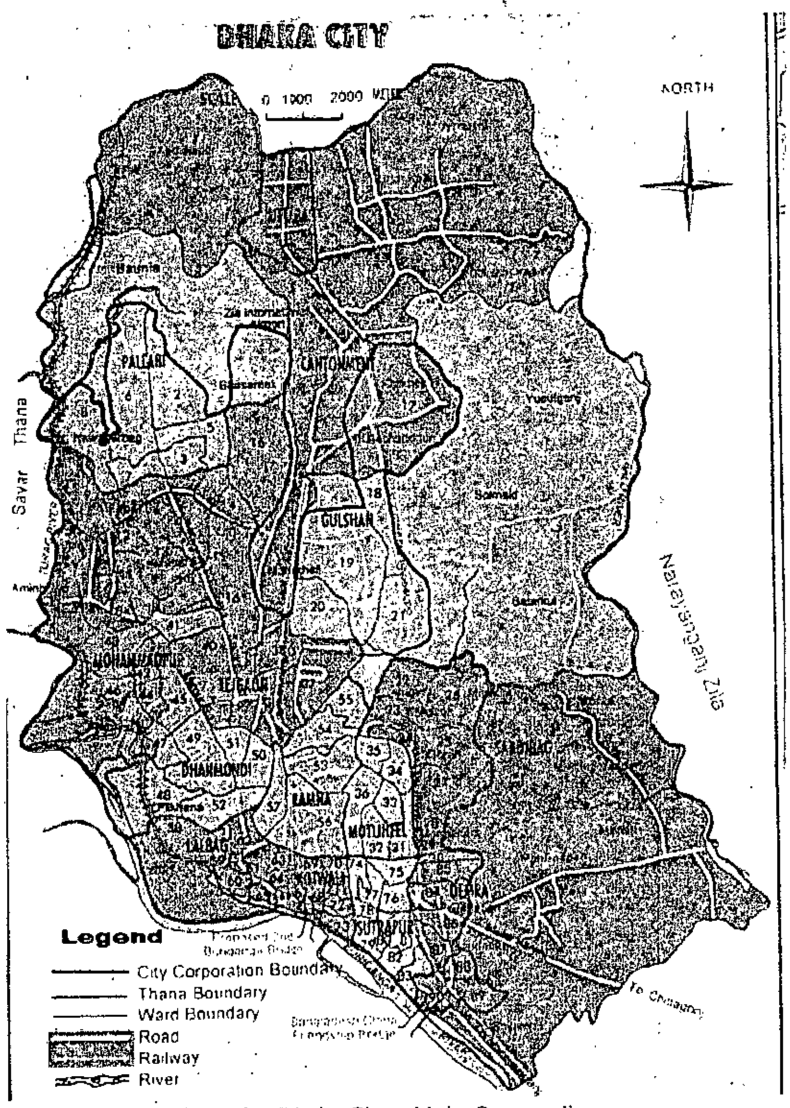

Figure 2.1 Dhaka City with its Surroundings
Source: www.deshimaps.com

Table 2.1 Air Temperature Profile of Dhaka City (Year 1950-1980)

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Ann
	Pre-Monsoon			Monsoon				Post-Mon		Winter			
Mean Max. Temp. (°C)	32.6	34.5	33.0	31.4	31.0	31.1	31.4	30.8	28.7	26.0	25.5	28.5	30.4
Mean Min. Temp. (°C)	19.7	23.5	24.8	25.8	26.2	26.1	25.9	23.7	18.2	13.3	11.7	14.5	21.1
Ave. Temp. (°C)	26.2	29.0	28.9	28.6	28.6	28.6	28.6	27.3	23.5	19.7	18.6	21.5	25.8

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

The temperature profile of the next decade (1981-1990) shows a slight fall of highest monthly mean maximum temperature by 1 °C in April. Fluctuation of average temperature in monsoon period is observed. Mean minimum and average temperature in January has increased by 1.5 °C and 0.9 °C respectively. Again increase of annual temperatures in all three categories should be taken into account.

Table 2.2 Air Temperature Profile of Dhaka City (Year 1981-1990)

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Ann
	Pre-Monsoon			Monsoon				Post-Mon		Winter			
Mean Max. Temp. (°C)	32.4	33.5	33.1	32.4	31.5	31.9	31.9	31.8	29.9	26.7	25.8	28.4	30.8
Mean Min. Temp. (°C)	20.5	23.5	24.6	26.3	26.3	26.5	26.0	24.0	19.3	14.7	13.2	15.8	21.7
Ave. Temp. (°C)	26.5	28.5	28.9	29.3	28.9	29.2	28.9	27.9	24.6	20.7	19.5	22.1	26.5

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

The more current data for the year 1991-2000 indicates some changes in magnitude of data from the previous sets of data. Pre-monsoon period accounts for higher maximum average temperature, while in April it is highest (34.0 °C) and the overall temperature profile of April has increased by .4 °C as compared to temperature profile of the previous decade. Mean maximum temperature in monsoon period indicates relatively higher temperature regime of over 31 °C as compared to previous one. In cold season, especially in January the average temperature is recorded as 18.8 °C and the mean minimum is 12.7 °C for the same month. Annual temperature profiles for both decades are of same magnitude (Table 2.3).

Table 2.3 Air Temperature Profile of Dhaka City (Year 1991-2000)

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Ann
	Pre-Monsoon			Monsoon				Post-Mon		Winter			
Mean Max. Temp. (°C)	32.6	34.0	33.2	32.7	31.8	31.9	32.1	32.0	29.8	26.6	25.0	28.0	30.8
Mean Min. Temp. (°C)	20.6	23.7	24.7	26.3	26.4	26.5	25.9	23.9	19.2	14.0	12.7	15.9	21.7
Ave. Temp. (°C)	26.6	28.9	29.0	29.5	29.1	29.2	29.0	28.0	24.5	20.3	18.8	21.9	26.2

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

Figure 2.2 shows the monthly mean maximum and minimum temperature profile for three time span as 1950-1980, 1981-1990 and 1991-2000; what is important is the fact that the annual average temperatures of last two decades has increased by .5 °C from 1950 to 2000

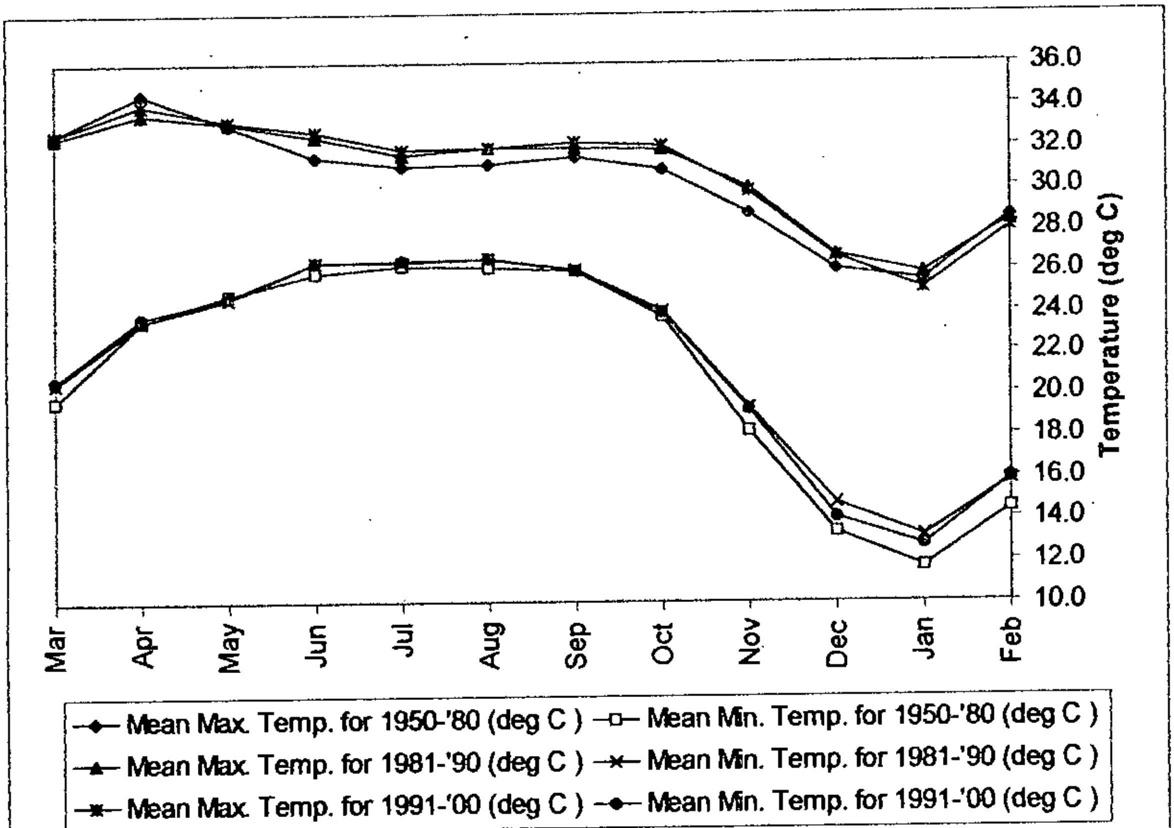

Figure 2.2 Monthly Mean Maximum and Minimum Air Temperature Profile for the Year 1950-1980, 1981-1990 and 1991-2000.

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

Based on the supplied data by Met. Office, highest ever maximum temperature in Dhaka was 42.3 °C, occurred on 30 March 1962 and the lowest ever minimum temperature was 4.5 °C recorded on 18 February 1953.

Overheating is a growing environmental concern for Dhaka. The problem is best illustrated by the probabilistic estimates based on data collected over a number of years.

Probabilistic Extreme estimates[1] for Dhaka predicts monthly highest maximum temperatures in April as high as 39.1 °C, 40.2 °C, 41.0 °C (in 1 year out of 4 years, 10 years and 25 years respectively), while the lowest minimum temperature in January are 7.4 °C, 6.4 °C, 5.6 °C (in 1 year out of 4 years, 10 years, 25 years respectively.) (Karmakar and Khatun, 1993). Recent meteorological observations in the pre-monsoon period a temperature of 36.5°C (1995) indicating a possible trend towards increased overheating due to Dhaka's inexorable urban growth. Furthermore observations made by Karmakar and Khatun (1993) and Hossain and Nooruddin (1993) indicates a noticeable variation in temperature in different parts of the city.

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[1] The period of observation is from 1961-'90. The probabilistic extremes are based on the equation $x' \approx \overline{x} \pm z.\sigma$ where x' is probabilistic estimate of the climatic variables, $\overline{x}$ is the mean value of the climatic variable, z is the standard deviation and represent z score or factor for the time scale. See Karmakar and Khatun (1993) for detail.

2.2.2 Relative Humidity

Relative humidities being a function of prevailing temperature are found to be inversely related to the urban heat island[2] intensity. Higher temperatures yield lower relative humidity level (all other conditions remaining the same). Humidity also varies depending on the density of the surrounding built form e.g. in Motijheel area, a major commercial district, a pocket of low humidity was observed in January where the heat island effect was maximum (Ahmed, 1995). The inverse relationship between relative humidity and temperature exists in heat island and warm pockets located away from water bodies. Warm pockets adjacent to Buriganga river have found high relative humidity. Investigation done by Hossain and Nooruddin (1993) indicates 2-4% in annual average relative humidity between Dhaka and adjacent rural areas. Another study indicates that with 50% impervious cover, runoff increases 200% compared with rural conditions concludes that urban humidity near the surface decreases due to the rapid run-off (Ahmed, 1994).

Urban, suburban and rural relative humidity exhibits a marked diurnal variation and generally decreases towards city center. During the afternoon in the dry seasons difference may be as high as 12% (Oguntoyinbo, 1984) and nocturnal difference can be as high as 13% in the same seasons.

Table 2.4 Monthly and Annual Mean Relative Humidity of Dhaka City for the Year 1950-1980, 1981-1990 and 1991-2000

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Ann
	Pre-Monsoon			Monsoon				Post-Mon		Winter			
Mean RH for 50-80 (%)	61.0	70.0	79.0	86.0	86.0	86.0	85.0	81.0	75.0	71.0	69.0	63.0	76.0
Mean RH for 81-90 (%)	65.0	73.8	78.7	84.0	86.4	84.3	84.6	78.6	73.1	73.8	71.7	64.3	76.6
Mean RH for 91-00 (%)	63.6	70.9	78.4	82.3	84.0	83.6	83.5	80.7	75.7	74.4	72.4	67.0	76.5

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

[2] Heat island phenomena are the result of urban/rural energy balance and stability differences, which in turn produce different rates of near surface cooling and warming (Lee, 1979) (Oke and Maxwell, 1975) (Unwin, 1980). The air in the urban canopy is usually warmer than that in the surrounding countryside. This urban heat island effect is probably both the clearest and the best-documented example of inadvertent climate modification. The exact form and size of this phenomenon varies in time and space as a result of meteorological, locational and urban characteristics.

According to data provided by the meteorological office of Dhaka, it has been found that the mean annual relative humidity between years 1950 to 1980 is 76%. Relative humidity is highest in monsoon season (86%) and comparatively low in winter season, while lowest being in March (61%). However, data for the next decade indicates rise of annual relative humidity by .6%, while during monsoon it decreases by almost 2%. Mean relative humidity is lowest for the month of February. From other set of data for the period between 1991 to 2000 the same source shows annual drop from the previous decade by .1%. The highest and lowest monthly mean values are 84% and 63.6% designated to July and March respectively. Interestingly except the middle period in other instances the lowest value of relative humidity is observed in March, which is in pre-monsoon season (Table 2.4). The humidity profile of all these three time-span illustrates the magnitude in almost same nature (Figure 2.3).

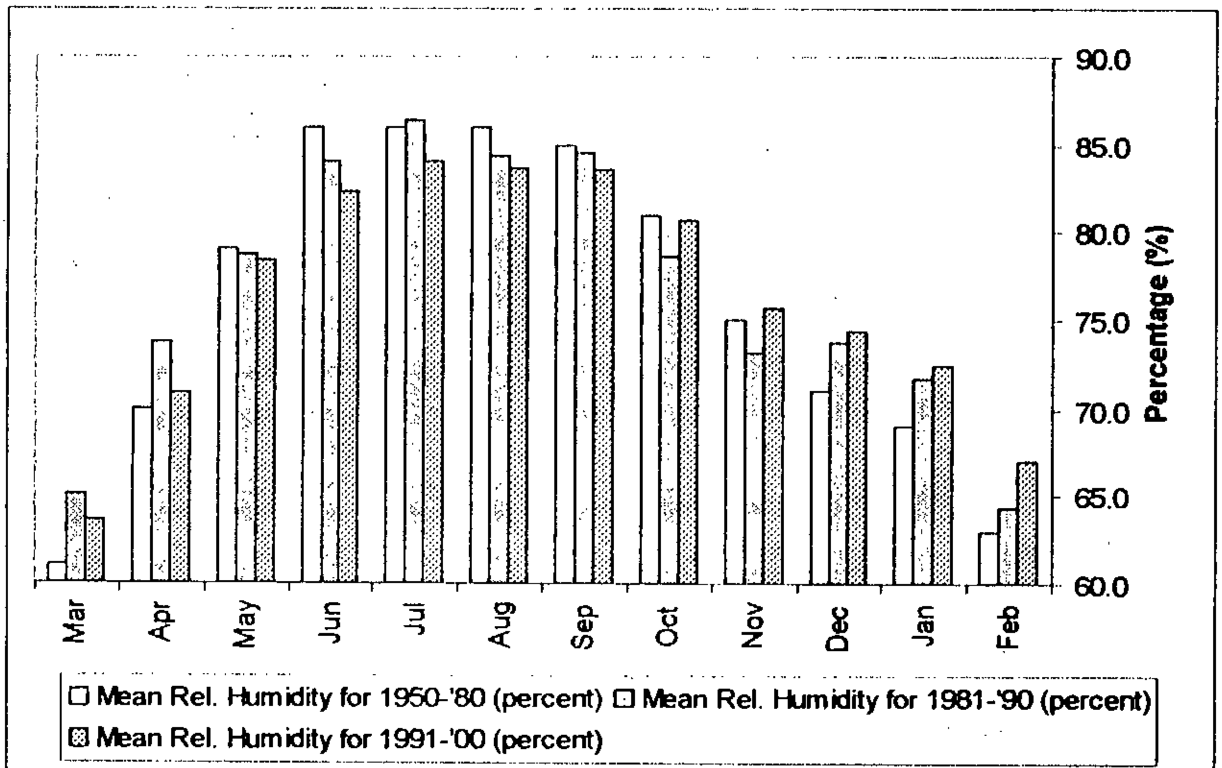

Figure 2.3 The Relative Humidity Profile of Dhaka City

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka. 2002

2.2.3 Rainfall

After a relatively dry winter, Dhaka remains under the grip of monsoon from June to September, a period that brings torrential rains. More than 75% of annual rainfall occurs in this period (Hossain and Nooruddin, 1993).

Table 2.5 Monthly and Annual Mean Rainfall of Dhaka City for the Year 1950-1980, 1981-1990 and 1991-2000

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Ann
	Pre-Monsoon			Monsoon				Post-Mon		Winter			
Mean Rainfall for 50-80 (mm)	69	120	258	397	386	326	264	158	26	8	12	20	2044
Mean Rainfall for 81-90 (mm)	81	199	302	357	377	269	348	159	52	12	6	23	2206
Mean Rainfall for 91-00 (mm)	69	120	342	267	371	335	293	197	26	13	11	27	2093

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

The total annual average rainfall for above three-time span exceeds 2000 mm, where highest rainfall (2206 mm) occurred between 1981-1901(Table 2.5). According to the monthly average total rainfall data (1950 - 1980), rainfall varies between 397 mm to 264 mm during the month of June and September respectively, while the minimum is recorded in December (8 mm). The next set of data for the time span between 1981-1990 indicates the same pattern of rainfall with highest intensity in monsoon period with highest monthly average in July (377 mm) and lowest in January (6 mm). In both cases one month shifting is observed. From more current data compiled between 1991-2000 it has been observed some fluctuation in rainfall between May and September (Figure 2.4). The magnitude of highest monthly average rainfall has changed but the time hasn't altered; where the maximum precipitation level in Dhaka city is in the month of July (371 mm) and the minimum in January (11 mm). So in three instance monsoon accounts for heavy rainfall which is far above than other seasons and clearly evident in Figure 2.4. Some of the extreme values can be presented here- the ever highest rainfall of 24 hours occurred on 14 July 1956 where the magnitude was 326 mm, while the heaviest rainfall of 1 hour was 85 mm recorded in 3March 1961.

Higher precipitations in comparison with the rural surroundings have been reported in Dhaka. This has been attributed to a phenomenon often observed in large urban areas. In such circumstances the air rises (due to increased buoyancy of the heated urban air) to the upper layer of the atmosphere, where the parcel of air cools until it can no longer hold moister and precipitates (Hossain and Nooruddin, 1993) (Padamanbhamurty and Bahl, 1984) (Geiger, 1961).

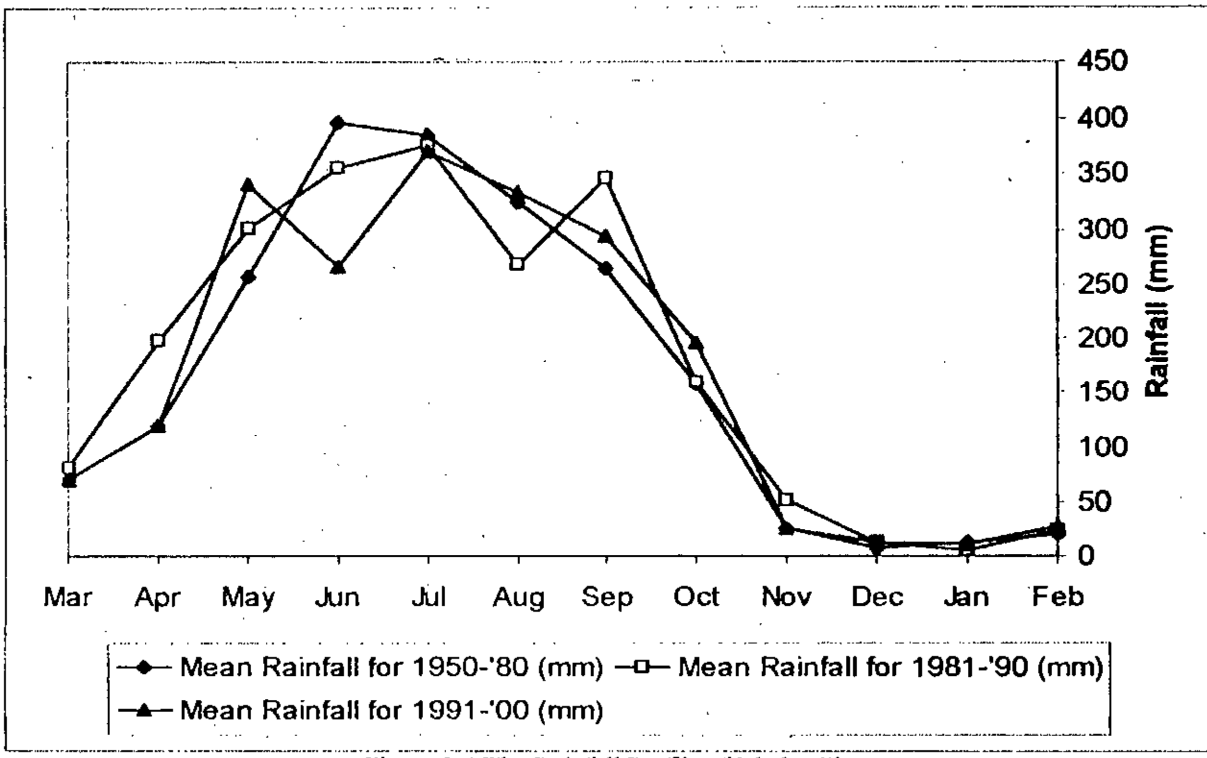

Figure 2.4 The Rainfall Profile of Dhaka City

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

Rainfall is one of the most important causes of internal flooding in Dhaka city and requires serious attention. This is due to the fact that large impermeable surfaces of the city create substantial runoff, while the existing drainage systems are incapable to cope with such magnitude of precipitation.

2.2.4 Wind Speed and Direction

The increases in surface roughness within cities cause reduction of wind speeds; mainly during the day (Jauregui, 1984). The variation in wind speed between meteorological station and site will depend largely on ground cover and topography. The wind speed is usually measured in flat open location (e.g. airport) at a height of 10 meter above ground level. To convert this to an equivalent wind speed at 3 meter in flat urban or sub urban locations, the wind speed must be multiplied by a reduction factor as shown in Table 2.6.This table illustrates the average reduction factor within dwellings with open windows facing the wind. These reduction factors will only give an approximate indication of the likely variation and will not be applicable in heavily built-up areas, close to high-rise buildings or major obstructions.

Table 2.6 Average reduction factors for Wind in different locations

Height	Location	Terrain		
		Open, flat unobstructed	Suburban or Wooded	Urban
10 m	In the open	1.0	0.5	0.3
	In building with cross ventilation	0.4	0.2	0.12
	In building with ventilation	0.15	0.07	0.04
3m	In the open	0.7	0.3	0.15
	In building with cross ventilation	0.3	0.12	0.06
	In building with ventilation	0.1	0.04	0.02

Source: Evans, M., 'Housing Climate and Comfort', The Architectural Press, London, 1980

In Dhaka where humidity ranges between 80% and 86% during hot-wet period, air flow plays an important role in thermal comfort. The meteorological data (1950-1980) based on conditions measured in open location (Table 2.7) shows that prevailing wind speed in Dhaka is comparatively high in monsoon period starting from June to September where the value is over 3 m/s and the highest being in July (4.2 m/s). The prevailing wind direction is south-easterly during this season; while the lowest speed is recorded in November and January (1.4 m/s) and wind direction is predominantly north-westerly for both months.

Table 2.7 Monthly Mean Prevailing Wind Speed and Direction of Dhaka City for the Year 1950-1980, 1981-1990

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
	Pre-Monsoon			Monsoon				Post-Mon		Winter		
Mean Wind speed for 50-80 (m/s)	2.8	2.8	3.9	3.3	4.2	3.9	3.1	1.7	1.4	1.9	1.4	1.7
Mean Wind speed for 81-90 (m/s)	2.4	2.9	2.4	2.3	2.2	2.2	2.1	2.1	1.3	1.6	1.4	1.9
Prevailing Wind Direction	SW	SW	S	SE	SE	SE	SE	N	NW	NW	NW	N

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

The prevailing wind direction in this period is south-westerly and south. Data for the next decade illustrates significantly low magnitudes of wind speed (Table 2.7). From March to October there is no significant variation in wind speed (2.1-2.9 m/s). Highest wind speed occurred in April (2.9 m/s) while lowest in November (1.3 m/s). Prevailing wind direction is same as for last thirty years.

As mentioned earlier that wind speed measurement varies considerably from place to place depending on orientation, 3 dimensional characteristic and vegetation and on level of measurement. Wind speed measurement in adjacent rural area has been found to be higher than Dhaka. Moreover wind speed and direction in open countryside is predictable, but in urban context these effects are almost totally unpredictable; because numerous obstructions are constantly modifying the prevailing wind direction and speed. The

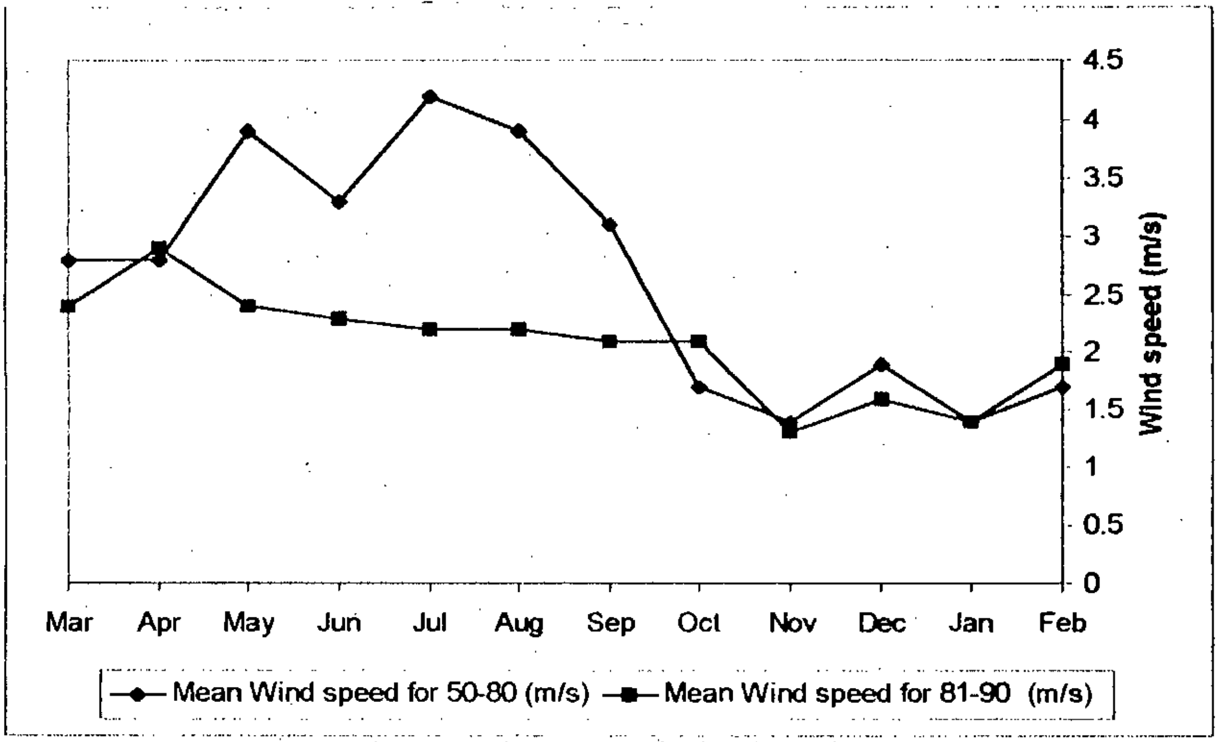

Figure 2.5 Wind Speed Profile for Dhaka City
Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

average wind speed is much lower in cities; Figure 2.5 testify this fact where the later data illustrates much lower average wind speed than data collected between 1950-1980. Rapid urbanization after 1980 plays a vital role in reduction of wind speed.

2.2.5 Solar Radiation

The microclimate or site climate is characterized by the amount of solar radiation received by that site and surrounding. Therefore, it is the single most deciding factor for assessing the climatic effects of the site due to its influence on temperature and density of air hence air speed and direction and humidity as well. The amount of solar radiation received by the site depends on the following factors (Koenigsberger et al, 1973):

i) Angle of incidence, ii) Atmospheric depletion i.e. iii) The absorption of radiation by ozone, vapors, iv) Duration of sunshine i.e. the length of daylight period, v) The material characteristics of the surroundings and vi) the site itself, i.e. absorption, reflection etc. of the site and surrounding.

Before 2000, radiation data were not collected regularly by the meteorological department of Dhaka and the raw data are not processed yet. However, radiation data recorded for 5 years at Joydevpur Agromet Pilot Station and for 7 years at Bangladesh University of Engineering and Technology by Mechanical Engineering Department are only available source to evaluate urban effect on incoming radiation (Huq and Hassan, 1993).

Data recorded at BUET is in urban context while meteorological data were collected in rural context. Higher diffused radiation usually observed in urban areas due to surrounding built form and hard surface quality. Therefore BUET data represent higher magnitude of global solar radiation. The comparison (Table 2.8) indicates that the difference between two measured values varies between 13% and 21%, which is in fact very high (Mojumder, 2000). Another reason high solar radiation in BUET may be that the air over the city being more polluted, results in a noticeable decrease in atmospheric clarity, causing a higher proportion of diffused radiation.

Table 2.8 Comparison of Monthly Global Solar Radiation between BUET and Meteorological Department of Dhaka

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
	Pre-Monsoon			Monsoon				Post-Mon		Winter		
Global Solar Radiation at BUET (kWh/m^2day)	4.66	5.05	4.55	4.01	3.65	3.75	3.75	3.60	3.61	3.15	3.25	4.01
Global Solar Radiation at Met. Office (kWh/m^2day)	3.41	3.53	3.04	2.79	2.61	2.56	2.48	2.69	2.49	2.30	2.51	2.61
Difference (%)	15	18	20	18	16	19	20	14	18	15	13	21

Source: Mojumder, A.U., *Thermal Performance of Brick Residential Buildings of Dhaka City*, M. Arch. thesis (unpublished), BUET, 2000.

Data provided by Ahmed (1994) indicates that horizontal surface receives highest amount of solar radiation (5329 Wh/m^2) in April and this value is fairly above than values of rest of the months. Intensity of solar radiation is also affected by angle of incidence (as mentioned earlier) and orientation; therefore it is reduced in vertical surface (Table 2.9). Table also shows that the direct radiations in the east and the west are higher than the north and south, while the north receives the lowest radiation, which is very negligible.

Table 2.9 Direct and Diffused components of Global Solar Radiation in Dhaka for the month of April.

	Global Radiation (Wh/m^2)	Diffused Radiation (Wh/m^2)				Direct Radiation (Wh/m^2)			
Hour	Horizontal	North	South	East	West	North	South	East	West
6	34	13	13	13	13	0	0	0	0
7	167	61	61	61	61	12	0	251	0
8	320	108	108	108	108	0	16	277	0
9	475	151	151	151	151	0	49	266	0
10	607	185	185	185	185	0	82	208	0
11	697	207	207	207	207	0	105	115	0
12	729	215	215	215	215	0	113	0	0
13	697	207	207	207	207	0	105	0	115
14	607	185	185	185	185	0	82	0	208
15	475	151	151	151	151	0	49	0	266
16	320	108	108	108	108	0	16	0	277
17	167	61	61	61	61	12	0	0	251
18	34	13	13	13	13	0	0	0	0
Total	5329	1665	1665	1665	1665	24	617	1117	1117

Source: Ahmed, Z. N., *Assessment of Residential sites in Dhaka with respect to Solar Radiation gain*, Ph.D. thesis (unpublished), 1994.

According to BUET data, in pre-monsoon period, particularly during the month from March to May, solar radiation on a horizontal surface is higher as compared to rest of the year and is maximum in April (5.05 kWh/m^2day). Higher ambient temperatures in these months indicate the causal link with such level of insolation. The insolation level is fairly constant between July to November, while the minimum is recorded in December (3.15 KWh/m^2day)(Table 2.8). Although there is a wide variation in monthly average extraterrestrial radiation during monsoon and post-monsoon period, cloudy atmospheric condition during these seasons result in the reduction (Figure 2.6). The clearness index during the month on June and July is considerably lower (0.35) compared to other months (highest observed in February around 0.5) as the incoming solar radiation is absorbed and reflected by the particles in the atmosphere and by clouds (Figure 2.6).

Therefore the diffused component of the radiation is significantly large and it is clear from the fact that in spite of a wide variation of sunshine hours, the total radiation incident on a horizontal surface has a comparatively marginal variation (Figure 2.7).

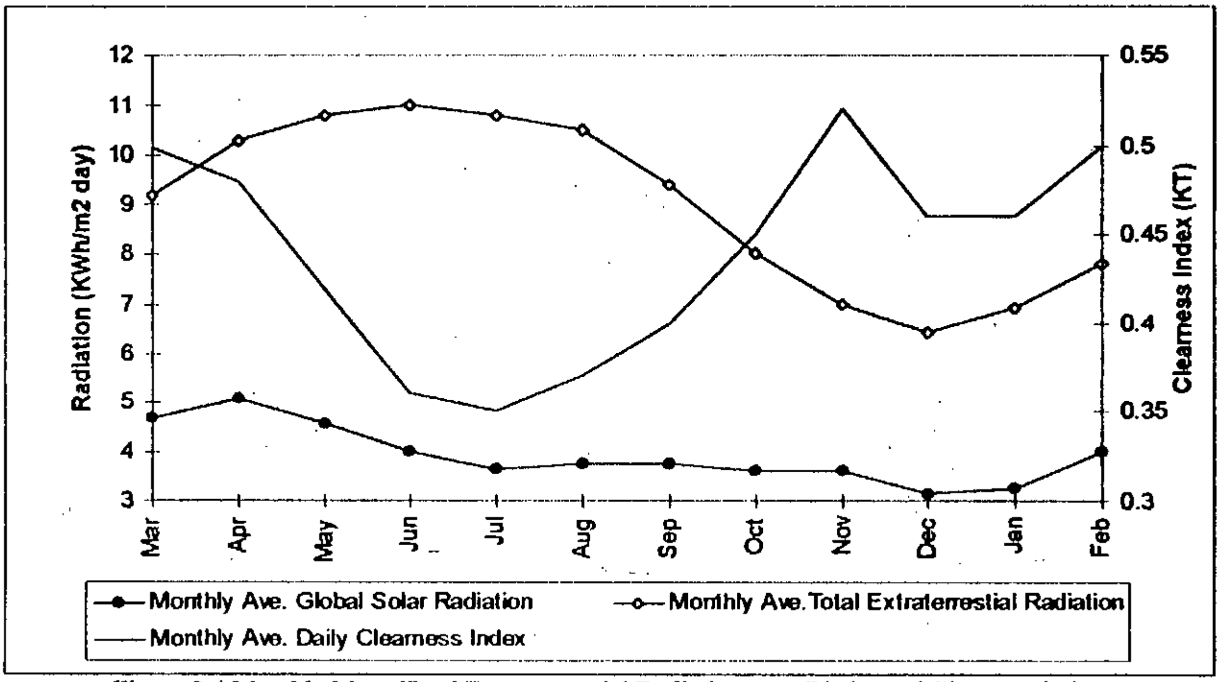

Figure 2.6 Monthly Mean Total Extraterrestrial Radiation over Dhaka and Clearness index.

Source: Huq, M.A., Hassan S.A., *"Global Solar Radiation on Horizontal Surface In Dhaka"*, Report of the Technical Conference on Tropical Urban Climates, World Meteorological Organization, Dhaka, 1993

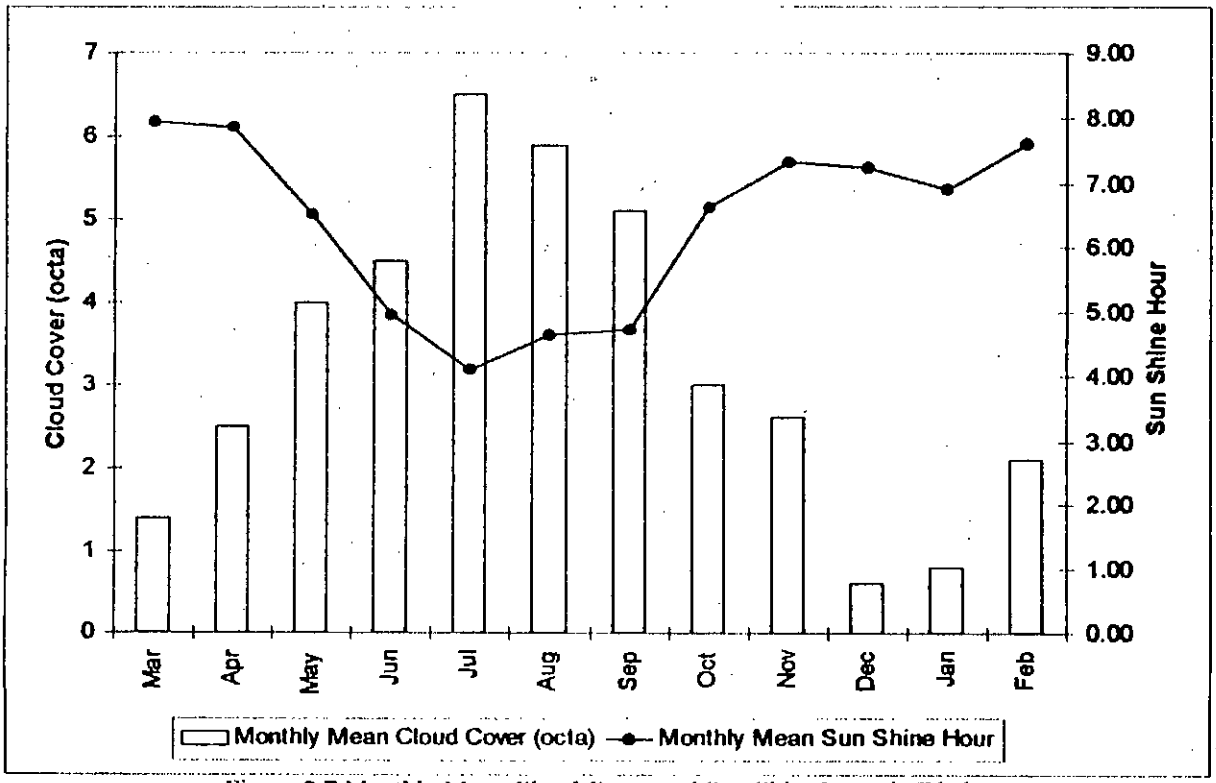

Figure 2.7 Monthly Mean Cloud Cover and Sun Shine hours in Dhaka

Source: Climate division, Bangladesh Meteorological Department, Agargaon, Dhaka, 2002

Another aspect of high cloud cover during those months over the city is that the long wave terrestrial radiation to the space is obstructed; particularly because of low and medium cloud formation. Moreover, the prevalence of low cloud that are most effective layer in obstructing terrestrial long wave radiation to the sky dome, are fairly constant. The potentiality to act as a thermal sink by the night sky is severely reduced by such cloud cover, hence during these months these diurnal difference in temperature are small.

2.3 THE IMPACT OF URBANIZATION ON CLIMATE

People are attracted to urban areas because they offer a host of socio-economic and cultural opportunities. This is especially true in many tropical and subtropical countries where urbanization is growing at an uncontrollable rate, which, in turn, deteriorates atmospheric environment (Taesler, 1991). Growth of cities introduces a profound modification of climate by human activities, which is not to be found any place else (Barry and Chorley, 1982).

The process of urbanization involves the construction of bridges, roads, underground drainage system, and factories, which radically transforms the radiative, thermal, moisture and aerodynamic characteristics of the pre-existing landscape, and thus creates climate of its own. As a result, more energy is received and retained, greenhouse elements (carbon dioxide, dust and other pollutants) are increased, and evaporative flux is lowered and sensible heat flux increased. Studies show that many large cities have experienced significant changes in cloudiness, precipitation, radiation and energy balance, temperature, air quality and visibility (Fortak, 1980) (Yonetani, 1982) (Cleugh and Oke, 1986) (Oke, 1982) (Nkemdirim, 1988). The extent of urban climate change varies from city to city, and it depends on the site and size of a city, landuse pattern, structure and density of buildings, traffic, industry, and other activities (Ahmed, 1993-b)

While the change in the global climate is likely to have grave implications for the rate of urbanization in devéloping countries like Bangladesh, urbanization will have some implications for the climate change itself thus reinforcing some of the factors giving rise to fast urbanization. The ways of urbanization as mentioned above can affect the climate, whether locally or globally. Urbanization generally leads to a drastic change in land use converting farmland into residential and commercial areas generally devoid of vegetation cover and thus increasing the albedo.

Urbanization leads to very high spatial concentration of energy use. Analysis by (Jones, 1992) using global data showed that a 1% rise in the per capita GNP leads to an almost equal 1.03 percentage increase in the consumption of energy. However, if the urban population increases by 1% the growth in consumption of energy is found to be 2.2%, i.e. the rate of change in energy use is twice the rate of change in urbanization. These results clearly indicate the effects that urbanization may have on energy use (Asaduzzaman, 1993).

In the developing countries, much of the energy is obtained from biomass for cooking purpose. With urbanization the pattern of energy use may not change substantially for the cooking purpose, but the use of other forms of energy, generally derived from fossil fuels, increase tremendously. These happen because urbanization and industrial concentration and the use of motorized vehicles is almost co-terminus. Such a change in the form of energy in use and their levels lead to a positive correlation between urbanization and emission of GHGs[1], a primary cause for global warming. Although the lifestyle of the people of Bangladesh is not energy-intensive as compared to developed nations, nevertheless the reduction in the consumption of non-renewable energy would entail a significant economic saving whilst having environmental benefits, among others a reduction of carbon-monoxide emission in the atmosphere.

Possible Climate Changes in the region: Definitive analysis of the future climate change in Bangladesh is lacking. But the scanning of the IPCC reports particularly the one prepared by the working Group I indicate (on the assumption of a doubling of CO_2 by the year 2030) the following effects on the climate of the region in and surrounding Bangladesh (Asaduzzaman, 1993):

There will be a general rise in surface air temperature, which is likely to be greater in percentage terms in winter than in summer.

Precipitation forecasts for winter seem to have a wider range from a reduction to an increase while during summers there may be up to 15% rise in rainfall.

Soil moisture forecasts seem to be quite uncertain but are likely to increase somewhat (up to 10%) during summer.

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[1] Green House Gases

Thus in general, the summers are likely to be somewhat more warm, more humid due to higher rainfall and the soil may be more moist. Winters are likely to be warmer, possibly drier and with possibly less soil moisture. There are also indications that the range of changes may be quite large especially for temperature. In fact the IPCC Working Group I predicts that the changes may take place at the upper and lower ends of the range keeping the mean values roughly the same as before. This means large year-to-year and inter-seasonal changes and increased frequency of both droughts and heavy rain and floods.

The City of Dhaka: Dhaka flourished as a center of commerce and administration in the Mughal period (1608-1764). During this period an early trend in the influx of population set in and continues to this date. Dhaka was a provincial capital of the then East Pakistan in 1948. After independence from Pakistan in 1971, Dhaka became the capital of Bangladesh, which is one of the most densely populated countries in the world. In 1948 Dhaka comprised of an area of approximate 50 sq. km and a population of approximately 250,000. By 1979 the population had grown to 3.5 million, considerably exceeding the capacity of the 1959 master plan. The area of the city now has grown to approximately 300 sq. km, with an estimated population of 7.4 million, thereby making it one of the top twenty most populated cities in the world (Linden, 1993). In spatial terms, the growth of the city did not match such unpredicted population growth, particularly after the independence. The trend continues with projections of 13 million by the year 2010 (Ahmed, 1995). Old Dhaka is characterized by very dense contiguous buildings usually 3-6 story tall, narrow streets, and very few open spaces or parks, while new Dhaka is characterized by a congested downtown with high-rise buildings, 5-6 story tall residential buildings, interspersed with newly constructed high-rise apartment buildings, relatively wider roads and more open spaces and some pockets of low-lying areas with perennial stagnant water.

The construction activities associated with roads, pavements and buildings increase radiation of heat. The high concentration of population and the nature of economic activities are generally higher levels of income also lead to high-energy consumption per capita and per unit of area. As a result heat island effect develops and in turn leads to higher use of energy to counter its effects (Asaduzzaman, 1993). Heat island intensities for Dhaka have been found to be 2.5 °K in January (winter), while it is insignificant in July, 0.6 °K (summer) (Ahmed, 1995). Urban Heat Island intensities are usually found to be highest early in the morning, when urban and rural surfaces are adequately cooled by means of long wave radiation evaporation and convection, hence temperature difference between urban and rural are most pronounced. During summer, the sky dome over Dhaka and its surrounding remain overcast with cloud, therefore in both cases the nocturnal cooling potential of the sky sink is reduced. Furthermore high surface winds in the city during summer have been identified as the major cause of Low Heat Island Intensity (Hossain and Nooruddin, 1993). While in the dry winter sky remains fairly clear and the rural areas cools down to a lower temperature as compared to urban area. Urban heat island investigations in mid latitude cities (Landsberg, 1981) (Oke, 1982) where urban geometry has been found to obstruct nocturnal cooling were in climatic regions marked by cloudless night skies. In such conditions the open rural areas cool down rapidly by long wave radiation. The complicated urban surfaces with reduced sky view cannot cool down at the sane rate as adjacent rural areas, hence leading to heat islands. However mean annual temperature, mean maximum and minimum temperature indicates that Dhaka has an urban heat island effect as shown in Table 2.10 The table reveals that the urban heat island affects the minimum temperature more than the both mean annual and the mean maximum temperatures.

Table 2.10 Comparison of Air Temperature between Dhaka City and its Suburbs (1961-1990)

Location	Mean Minimum Temperature (°C)		Mean Maximum Temperature (°C)		Mean Annual Temperature (°C)	
	Temperature	Difference	Temperature	Difference	Temperature	Difference
Dhaka City (urban)	21.4	0.5	30.6	0.4	25.8	0.4
Tangail (rural)	20.9		30.2		25.4	

Source: Hossain, M.E., Nooruddin, Md., *"Some Aspects of Urban Climate of Dhaka City"*, Report of the Technical Conference on Tropical Urban Climates, World Meteorological Organization, Dhaka, 1993

2.4 CONCLUSION

Although for most of the period overheating is a major environmental concern for Dhaka, the nature of the problem is dictated by the combination of the environmental factors in the ambiance during those period, i.e. overheating with humid or dry condition. The nature of the overheated condition of Dhaka can be identified from the discussion presented in the preceding chapter on urban climatic factors and their magnitude different time of the year.

Table 2.11 compares the environmental variables for the whole year and illustrating their potential impact on the climate. It is observed that pre-monsoon period (March to May) is characterized by very high air temperature and solar radiation where potential for nocturnal cooling is also high, while June to October with very high relative humidity and precipitation associated with high temperature and in the months July to August due to high cloud cover nocturnal cooling potential is reduced considerably. In case of the former, reducing the impact of solar radiation can substantially moderate overheating condition and in case of the later, optimizing airflow can play a vital part towards moderation. Humid condition with high ambient temperature is often the most lasting environmental condition in wet tropics like Bangladesh.

The scope of this thesis in terms of the issue raised in the environmental agenda is limited, and this work focuses on the thermal performance of operable roof insulation where performance is accessed by thermal comfort and particularly comfort of the indoor. The primary concern of this chapter is to develop an understanding of the urban climate of Dhaka and the basis for other relevant environmentalconcernsand also for simulation studies and field work (discussed in the later chapters of this work).

Table 2.11 The Environmental Matrix of Dhaka

	Air Temp.	Radiation	R. Humidity	Nocturnal Cooling Prospect
January				X
February				X
March	◘	◘		◘
April	◘	◘	●	◘
May	◘	◘	●	◘
June	●	○	◘	●
July	●	○	◘	○
August	●	○	◘	○
September	●	○	◘	○
October	○	○	●	●
November				X
December				X

Legend: ◘ very high ● high ○ moderate, blank cells indicate low value X not required

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CHAPTER THREE

INDOOR COMFORT AND ISSUES

3.1 INTRODUCTION

The ambient environment has both a physical and emotional effect on human being and is therefore of principal importance in building design. One of the architects/designers main tasks is to create a comfortable environment inside the building, which is appropriate for all the human activities likely to take place there. It is a challenge for the designers to strive towards the optimum of total comfort, which may be defined as the sensation of complete physical and mental well being (Koenigsberger et al 1973) (Goulding et al 1992). Thus defined, it is only to a limited extent within the control of the designer. The occupants' physical, biological, and emotional characteristics also come into play. Hence if a group of people is subjected to same climate, the individual members are unlikely to be satisfied concurrently. Although, the notion of a comfortable environment for all would encompass the consideration of individual preferences, still there are a set of general conditions in which a majority of people would feel comfortable; where the determinants are air and radiant temperature, humidity, airflow etc. A number of attempts have been made to determine the values of these variables. Developing and understanding of the issue of comfort, the following chapter appraise these conditions on the basis of existing knowledge.

3.2 DEFINITIONS AND CONCEPTS

Comfort is not completely a sensory phenomenon but largely one of perception (Fisher, 1978) (Bansal, 1994). While sensations like smell, sound, light, temperature and pressure being at physiological level, the experiences do not conclude at sensory level, but at the level of perception. Perception of these individual sensations are often subjected to short as well as long term conditioning, caused by a wide range of influences. These influences may be developed from psycho-physical to socio-cultural framework of an environment. Therefore disparities in comfort perception are observed among the rural and urban population and among developing and developed countries (Ahmed, 1995).

Comfort is generally defined in terms of a number of environmental factors like air temperature, radiant temperature, air flow, relative humidity and their effect is synergistic.

Thermal comfort can be defined operationally as the range of climatic conditions considered comfortable and acceptable inside buildings. It implies an absence of any sensation of thermal (heat or cold) discomfort (Givoni, 1998).

The definitions of thermal comfort emphasis on the notion of thermal neutrality i.e. the conditions under which the human body is in a state of thermal equilibrium with its surroundings (Fanger, 1970) (Burberry, 1983) (Edholme et al, 1985). But attainment of thermal neutrality doesn't necessarily ensure comfort. For example, a person who is exposed to an asymmetric radiant field may well be in thermal neutrality but is unlikely to be comfortable. In most situations encountered in buildings, however, the two conditions will coincide (Goulding et al, 1992).

According to American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) after an extensive study defines thermal comfort as that condition of mind, which expresses satisfaction with the thermal environment (ASHRAE, 1958). Factors associated with olfactory, acoustic and visual environment can considerably influence thermal comfort judgment (Nanda, 1989, reported by Ahmed, 1995)

In terms of occupants in a building it is best defined as the conditions where most of the people are unaware of the thermal conditions around them and do not feel the need to adjust to it (Mallick, 1994). Comfort is influenced by geographic location and long-term acclimatization to a particular environment. Cultural difference account for different preferences (Carmona, 1986 ; Fathy, 1986; reported by Ahmed, 1995)

With regard to the human body's thermo-regulation, comfort is defined as the state where the body maintains a thermal equilibrium without restore to the regulatory mechanisms. Thus it is a state, which accompanies minimal energy use to maintain thermal equilibrium (Lowry, 1991). The thermal equilibrium is observed with respect to the almost constant temperature of 37 °C, within +/- 1 °C and usually designated as 'set-point' temperature. This temperature is maintained in the brain, heart and in the abdominal organs. The skin temperature maintains a temperature range between 31 to 34 °C, which varies with respect to ambient conditions and metabolic rate.

Comfort in the larger and real sense, embrace aesthetic and psychological factors such as quality of light, vegetation, landscaping, safety, prestige etc., all the more so because these are determined historically and are often the determining factor in choice which could otherwise be incomprehensible (Mojumder, 2000).

3.3 FACTORS INFLUENCING THERMAL COMFORT

Among the factors that influence thermal comfort, some of them depend on the condition of the environment and their effect can be directly perceived by the human body and can also be expressed in quantifiable terms; therefore they can be controlled. While other factors are innate or deductible from socio-cultural point of view and for that matter designers cannot control them directly. Followings are the categories of factors that influence thermal comfort:

- Physiological factors
- Behavioral factors
- Environmental factors

3.3.1 Physiological Factors

Metabolic rate: Heat is continuously produced by the body. Majority of the biochemical processes involved in tissue building, energy conversion and muscular work are exotherm, i.e. heat producing. All energy and material requirements of the body are supplied from the consumption and digestion of food. The process involved in converting foodstuff into living matter and useful form of energy are known as metabolism (Koenigsberger et al, 1973).

The metabolic rate of the body, that is the rate at which it produces energy, increases with the body's activity. It can be measured in watts per square meter or in mets, where 1 met is the metabolic rate of a person sitting, inactive, in a room with still air; it is approximately 58 W/m^2. The metabolic rate of various activities are given in Table 3.1 and Figure 3.1

The metabolic rate varies with the surface area of a person's skin. This is determined by an empirical formula derived by D. and E.F. DuBois (DuBois, 1915).

Table 3.1 Typical metabolic heat generations for various activities

Activity	W/m²	met
Resting		
Sleeping	40	0.7
Reclining	45	0.8
Seated, quiet	60	1.0
Standing, relaxed	70	1.2
Walking (on the level)		
0.89 m/s	115	2.0
1.34 m/s	150	2.6
1.79 m/s	220	3.8
Office Activities		
Reading, seated	55	1.0
Writing	60	1.0
Typing	65	1.1
Filing, seated	70	1.2
Filing, standing	80	1.4
Walking about	100	1.7
Lifting, packing	120	2.1
Driving/Flying		
Car	60-115	1.0-2.0
Aircraft, routine	70	1.2
Aircraft, instrumental landing	105	1.8
Aircraft, combat	140	2.4
Heavy vehicle	185	3.2
Miscellaneous Occupational Activities		
Cooking	95-115	1.6-2.0
House cleaning	115-200	2.0-3.4
Seated, Limb movement	130	2.2
Machine work		
Sawing (light table)	105	1.8
Light (electrical industry)	115-140	2.0-2.4
Heavy	235	4.0
Handling 50 kg bags	235	4.0
Pick and shovel work	235-280	4.0-4.8
Miscellaneous Leisure Activities		
Dancing, social	140-255	2.4-4.4
Calisthenics/exercise	175-235	3.0-4.0
Tennis, singles	210	3.6-4.0
Basketball	290-440	5.0-7.6
Wrestling, competitive	410	7.0-8.7

Source: *Energy in Architecture (The European Passive Solar Handbook)*, B.T. Bats Ford Limited, 1992

Higher heat production is the result of higher metabolic rate, which help the ability to feel comfortable during cold, while increasing the sensation of discomfort at higher temperatures. The metabolisms of aged people are slower, for that matter they usually prefer higher temperature. In warm climates when thermal discomfort is felt with the increase of metabolic rate, requirement of lower skin temperature is increased (Givoni, 1989). Mechanisms of excess heat production within the body are inhibited in overheated situations. According to the studies conducted in various climatic zones show that metabolic rates are much as 10 to 20% lower in the subjects of the tropical regions than that of arctic regions (Guyton, 1991) (Bray, 1985).

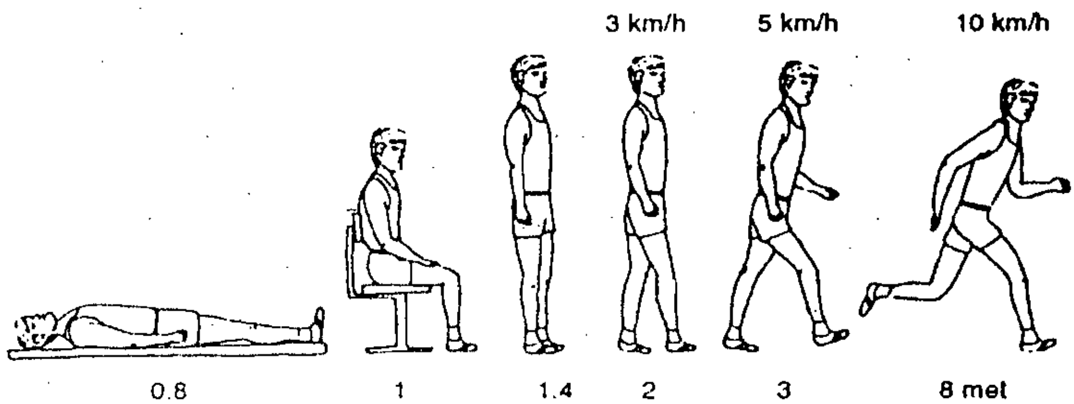

Figure 3.1 Metabolic rate of different activities
Source: *Energy in Architecture (The European Passive Solar Handbook)*, B.T. Bats Ford Limited, 1992

Acclimatization: Acclimatization to ambient environmental condition is a major factor as it appropriately adjusts the threshold of relative temperature tolerance of a person (McIntyre, 1980). Therefore heat acclimatization, namely physiological adaptation to a hot climate or to "artificially" induced heat stress, has an important role in the susceptibility to the physiologically harmful effects of heat and to the sensory discomfort caused by hot environment (Givoni 1998). A person when exposed to hot environment generally acclimatizes within 1 to 6 weeks. This adaptive mechanism results in abundant sweating and lowering metabolic rate which in turn increases the potential of heat loss by evaporation. As a result sweating often increases to a maximum of 2 litter/hour and has the heat removal potential of more than 10 times the production of the normal basal rate (Guyton, 1991).

Givoni and Goldman (1973) have studied the quantitative physiological mechanism of heat adaptation. The main physiological manifestation of improved heat tolerance are a higher sweat rate (providing more evaporative cooling) and lower inner body temperature and heart rate, indicating lowering of the physiological strain imposed by a given heat stress (Givoni, 1998). Although this form of adaptation happens after long exposure to a set of climatic conditions, it is not static. In other words, the influence of acclimatization on thermal comfort may change with the change of seasons within a same climatic region.

State of Health: State of health influences thermal requirements. During illness the metabolic rate may increase, but the proper functioning of the regulatory mechanism may be impaired. The tolerable range of temperature will be narrower and irregular in this situation.

Food and Drink: Metabolic rate can be affected by certain kind of food and drink. This may be a cause for difference in diet between tropical and arctic peoples.

Skin Color: This may influence radiation heat gain. The darker the skin color, the higher the radiation heat gains. The albedo of black skin is about 0.18 while for white skin it is 0.35. With a black skin, the penetration depth of solar radiation (short wave band) in maximum of 0.4 mm (i.e. it is contained near the surface where it is lost easily) and in case of white skin it penetrates 2 mm (i.e. taken into the blood and contributes towards heat storage). For the former, it doesn't cross the depth of the dermis and in the later case it penetrates well into the dermis (Oke, 1978).

3.3.2 Behavioral Factors

Behavioral control or 'psychological adaptation' (Baker, 1994) (Nicol, 1994) (Berger, 1990) to the thermal conditions to achieve comfort is one of the most important avenues and it is the only effective path for controlling body temperature in severely cold environments. Whenever the body temperature crosses the controllable limit, a 'physic signal' of being overheated is transmitted from the brain, which compels a person to make necessary adjustment to recover comfort (Ahmed, 1995).

Clothing: Thermal comfort is greatly affected by clothing, which is an important mode of behavioral control of temperature. Social and religious conventions impose limitations on the amount of clothing that can be shed in hot weather, and practical considerations inflict limits on the protection that can be given to the face, the hands and the feet in very cold weather. However, clothing can be of enormous help in creating comfortable conditions. By changing the type of cloth or by buttoning or unbuttoning a person can adjust to thermal stress to a certain limit.

Clothing is taken as an insulating medium next to skin in human energetic evaluation. It impedes heat loss through conduction and convection by entrapment of air next to the skin and in its weave. Radiation loss is also affected by weave of the clothing and it can occur through the intervening spaces of the fabric or be obstructed by a closely-knit fabric and re-radiate to the skin (Ahmed, 1995).

The thermal resistance of clothing can be expressed in terms of m^2K/W or clo units. 1 clo corresponds roughly to the thermal resistance of a winter business suit, i.e. 0.155 m^2K/W (Goulding et al, 1992) (Cowan et al, 1983) (McIntyre, 1980). In tropical environments typical clothing varies approximately between 0.35 to .5 clo. This clothing expedites evaporative heat loss by acting as a mess and also allows wind action directly on the skin in hot humid environment (Ahmed, 1995). The thermal insulation properties of various types of clothing are given in Figure 3.2 and Table 3.2

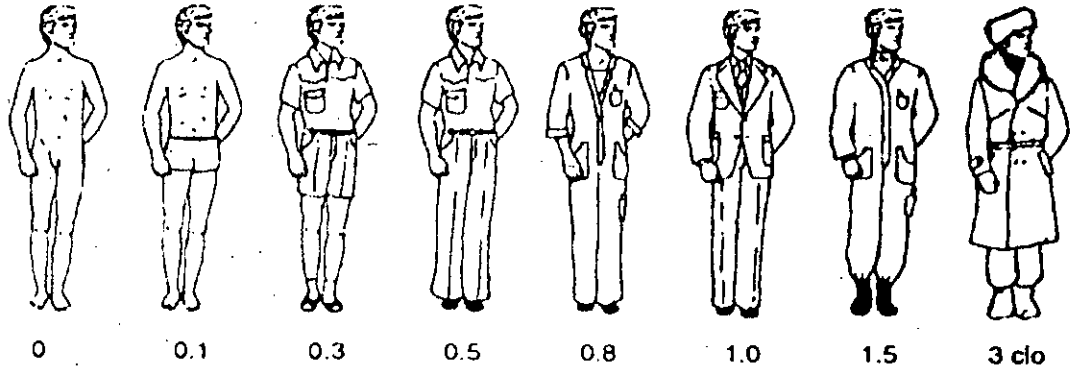

Figure 3.2 Thermal insulation properties of typical combinations of clothing
Source: *Energy in Architecture (The European Passive Solar Handbook)*. B.T. Bats Ford Limited. 1992

The maximum clothing, which could be worn in the house without restricting movement for normal household activities, is just over 1 clo unit. A reasonable range to ensure both decency and unrestricted movement is between 0.5 to 1.0 clo (Mojumder, 2000).

Social factors: An environment may be perceived comfortable to a particular social class or a society, while the same environment may seem to be uncomfortable to other society or social class. The reason for this phenomenon is that- the expectation of comfort level varies from society to society with changing in affordability, e.g. expectation range of thermal level of higher income group of people varies with the lower or middle-income social groups. It has been observed that people from higher income group often demonstrate more exacting comfort requirements than a group from lower income strata. People's expectation increases as the means to achieve comfortable environment come within the reach (Mojumder, 2000).

Table 3.2 Thermal insulation provided by various combinations of clothing.

CLOTHING	THERMAL RESISTANCE	
	m^2 K/W	clo
Nude	0	0
Shorts	0.015	0.1
Typical tropical clothing ensemble: Briefs, shorts, open-neck shirt with short sleeves, light socks and sandals	0.045	0.3
Light summer ensemble: Briefs, long light-weight trousers, open-neck shirt with short sleeves, light socks and shoes.	0.08	0.5
Light working ensemble: Light underwear, cotton work shirt with long sleeves, work trousers, woolen socks and shoes.	0.11	0.7
Typical indoor winter ensemble: Underwear, shirt with long sleeves, trousers, jacket or sweater with long sleeves, heavy socks and shoes.	0.16	1.0
Heavy traditional European business suit: Cotton underwear with long legs and sleeves, shirt, suit including trousers, jacket and waistcoat, woolen socks and heavy shoes.	0.23	1.5

Source: *Energy in Architecture (The European Passive Solar Handbook)*, B.T. Bats Ford Limited,1992

3.3.3 Environmental Factors

The primary environmental factors that affect thermal comfort are Air Temperature, Radiant Temperature, Relative Humidity and Air Flow. These environmental factors are quantifiable individually unlike some physiological or behavioral factors. Their effect on comfort perception is synergistic. Therefore in case of indoor environment all these factors may contribute to a thermal perception and therefore control or regulation of one or two of them can considerably modify the impact of others.

Air Temperature: Temperature is the main criterion of human comfort. It is difficult to be comfortable at a temperature higher than the central body temperature of 37 °C (Cowan et al, 1983). In order to maintain body temperature at this level, all surplus heat needs to be dissipated to the environment. If there is some form of simultaneous gain of heat from the environment, that must be dissipated also. The air temperature determines the convective heat exchange between skin and ambient air.

The average skin temperature in indoor situation is about 33 to 34 °C. With lower air temperature the body looses heat and with higher temperature body gains heat by convection. The rate of convective heat exchange depends on airspeed (roughly proportional to the square root of the speed). It is greatly affected by the insulation value of the clothing (the clo value).

Radiation and Mean Radiant Temperature (MRT): All thermally excited surfaces in an environment emit radiation (for more detail see chapter four) in different directions and the radiant temperature indirectly indicates the radiation field and its intensity. The thermal receptors of human body are directly excited by short as well as long wave radiation. For that matter radiation level is a factor to be considered in comfort evaluation. Although all bodies exchange heat by radiation continuously, heat gain or loss by this process is determined by the net effect of all the losses and gains. Thus heat loss by radiation is negative when the surrounding surface temperatures are above skin temperature, accordingly a person emits less heat in comparison to the amount gained from the surrounding surfaces.

Another aspect of radiation on comfort is the possible effect of asymmetric radiation or radiant asymmetry. Results obtain for long wave radiation in studies conducted by Fanger et al for interior suggests that a radiant asymmetry at a warm wall cause less discomfort than a cool wall. A cool ceiling causes less discomfort than warm ceiling al (Fanger et al, 1985) (Olsen et al, 1973). This phenomenon is important when the radiation from the underside on an overhead shading plane is considered (particularly roofs).

Mean radiant temperature is defined as follows- if all surfaces in an environment were uniformly at this temperature; it would produce the same net radiant heat balance as the given environment with its various surface temperatures (Koenigsberger et al 1973).

The mean radiant temperature is an average temperature of the surrounding surfaces (Figure 3.3). It includes the effect of incident solar radiation and has a great impact on human comfort as air temperature (Goulding et al, 1992). Mean radiant temperature of the indoor determines the radiant heat exchange between skin and the environment. Low radiant temperatures can contribute to the cooling of the body even if the air temperature is high (Mallick, 1994).

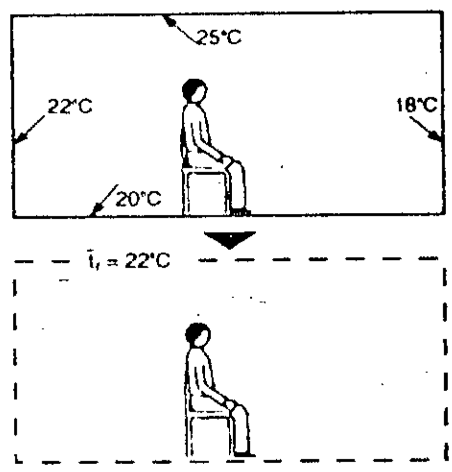

Figure 3.3 the concept of Mean Radiant Temperature (after Goulding et al, 1992)

Relative Humidity: The impact of relative humidity on human thermal balance and on comfort is complex. Humidity doesn't directly affect the heat balance and the sensory or physiological responses to the thermal environment, except for the evaporation within the lungs. The role of relative humidity is in its effect on the environmental potential for evaporation and the process by which the body adapts to changes in the evaporative potential. The evaporative capacity of the air is a function of air humidity and air speed.

Very low humidity may cause irritation where the skin becomes too dry and cracks may appear in some membranes like lips. At higher humidity level its effect on human comfort and physiology is indirect, although its effect on the evaporative capacity of the air. A higher humidity reduces the evaporative cooling potential from a given surface area of the skin, but the body can counter this reduction by spreading the sweat over the skin and thus increasing the fraction of the skin surface from which evaporation takes place. As a result of this physiological control mechanism the same amount of sweat evaporation, and of evaporative cooling can be obtained over a wide range of humidity (Givoni, 1998).

Air Flow: The effect of air flow on comfort depends on the environmental temperature and humidity as well as on clothing. At temperature below about 33 °C, increasing air flow reduces heat sensation due to higher convective heat loss from the body and the lowering of the skin temperature. A temperature between 33° and 37 °C, air flow doesn't affect significantly the thermal sensation, although it might have very significant effect on discomfort from excess skin wetness, depending on the humidity level and the type of clothing. At temperature above 37 °C, increase air velocity actually increase the thermal sensation of heat, although it still reduces skin wetness and so might be desirable. Alleviation of discomfort due to skin wetness is best achieve (without dehumidification) by maintaining a high-enough air flow over the body, so that the required evaporation can be achieved with a smaller wetted area of the skin (Givoni, 1998).

Apart from the thermal effect, air flow has certain mechanical effects, which can be described, by discomfort levels. Table 3.3 provides a summary of effects produced by air motion based on extended Beaufort scale (Koenigsberger, et al, 1973)

Table 3.3 Velocity effects on people, tabulated at 10 meter height.

Beaufort Number	Description	Air velocity (m/s)	Effect
2	Light Breeze	1.6-3.3	Pressure felt on face
3	Gentle Breeze	3.4-5.4	Hair disturbed, clothing flaps, newspaper difficult to read
4	Moderate Breeze	5.5-7.9	Raises dust and loose paper, hair disarranged
5	Fresh Breeze	8.0-10.7	Pressure felt on body, possible stumbling when entering windy zone
6	Strong Breeze	10.8-13.8	Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, wind noise on ears unpleasant
7	Near Gale	13.9-17.1	Inconvenience felt when walking
8	Gale	17.2-20.7	Generally impedes progress, great difficulty with balance in gusts
9	Strong Gale	20.8-24.4	People blown over

3.4 THE COMFORT ZONE

The concept of comfort zone within an ambience is described with respect to a combination of environmental variables where a majority of people may feel comfort. By virtue of this zone, comfort conditions can be expressed in terms of combination of factors like temperature, relative humidity, air flow etc. instead if a single parameter (Ahmed, 1995).

The ASHRAE comfort zone is drawn on a conventional psychometric chart. It specifies boundaries of air temperature and humidity for sedentary people. It was constructed mainly for use in air-conditioned office buildings but is also used in evaluating indoor climates I residential buildings (Givoni, 1998). Although the psychometric is suitable to describe comfort condition where skin wetness is important factor. It has limitation in humid conditions where higher velocity of air is accepted and acclimatization is an important determinant (Ahmed, 1995). Olgay (1963) first developed a bioclimatic chart (Figure 3.4) where the notion of comfort zone is defined in terms of dry bulb temperature as ordinate and abscissa respectively. The comfort zone is plotted on a chart. It is bounded by a fixed lower temperature (21°C) and by a humidity dependent upper limit. At relative humidities below 50 % the upper comfort limit is 27.8 °C. At relative humidities above 50% the upper temperature limit drops down gradually, until it intersects with the lower limit at 90 % relative humidity (Givoni, 1998). Later the chart was modified by Szokolay (1984), Arens (1980) and Givoni (1982). Sharma and Ali (1986) (Figure 3.5) in their study of Indian subject suggested temperatures above 30 °C for comfort although upper limit of relative humidities are restricted to 70 %. Mallick (1994) has developed summer comfort zone for Bangladesh

<u>Summer Comfort Zone</u>:

The evaluation of comfort conditions is based on the analysis of air temperature and relative humidity values. According to the research conducted by Mallick (1994) air temperature for comfort with no air movement and for people wearing normal summer clothing, engaged in normal household activity indoors are within the range of 24 °C and 32 °C and for relative humidities between 50% and 95%.

In still air condition people feel comfortable even in higher humidities, which is expected response in a location where humidity is generally high for most of the year. With the introduction of air flow relative humidity up to 95% is tolerated.

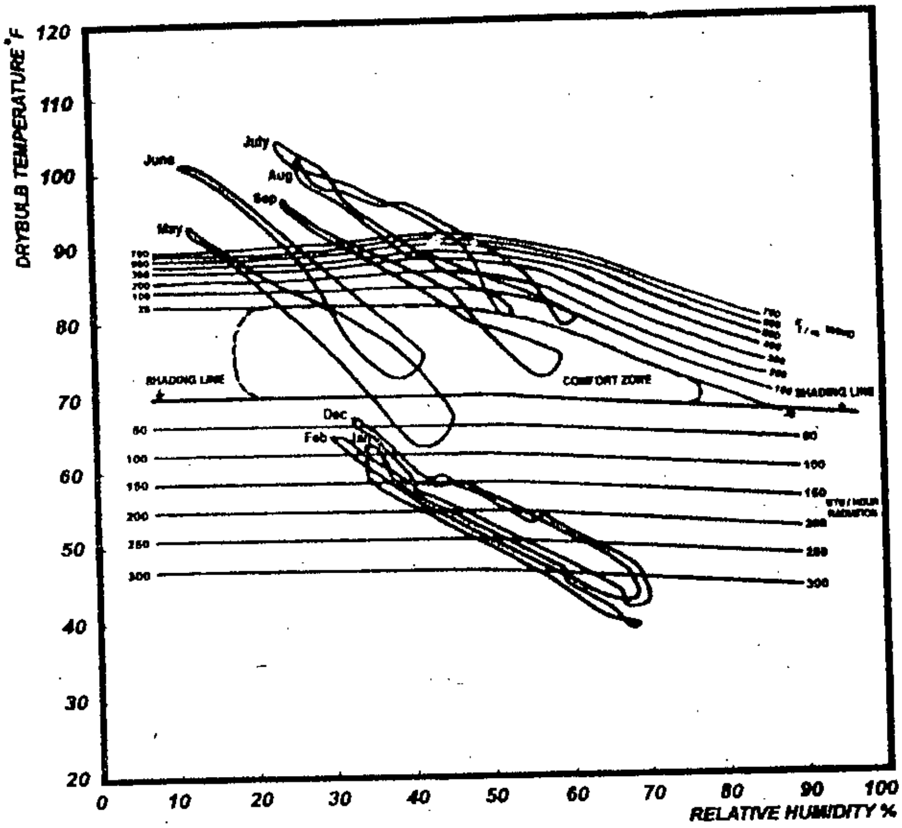

Figure 3.4 Olgyay's Bio-Climatic chart

Source: Givoni, B., *Climate Considerations in Buildings and Urban Design*, Van Nostrand Reinhold Company, 1998.

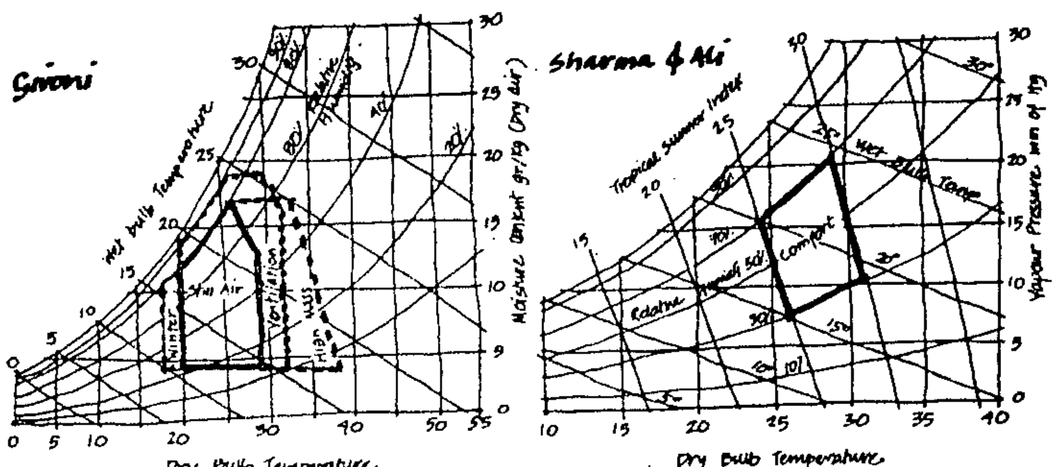

Figure 3.5 Adaptation of comfort zone in warm climates (after Givoni, Sharma and Ali)

Source: Mallick, F.H., *Thermal Comfort for Urban Housing in Bangladesh*, Ph.D. thesis (unpublished), A.A. School of Architecture, 1994.

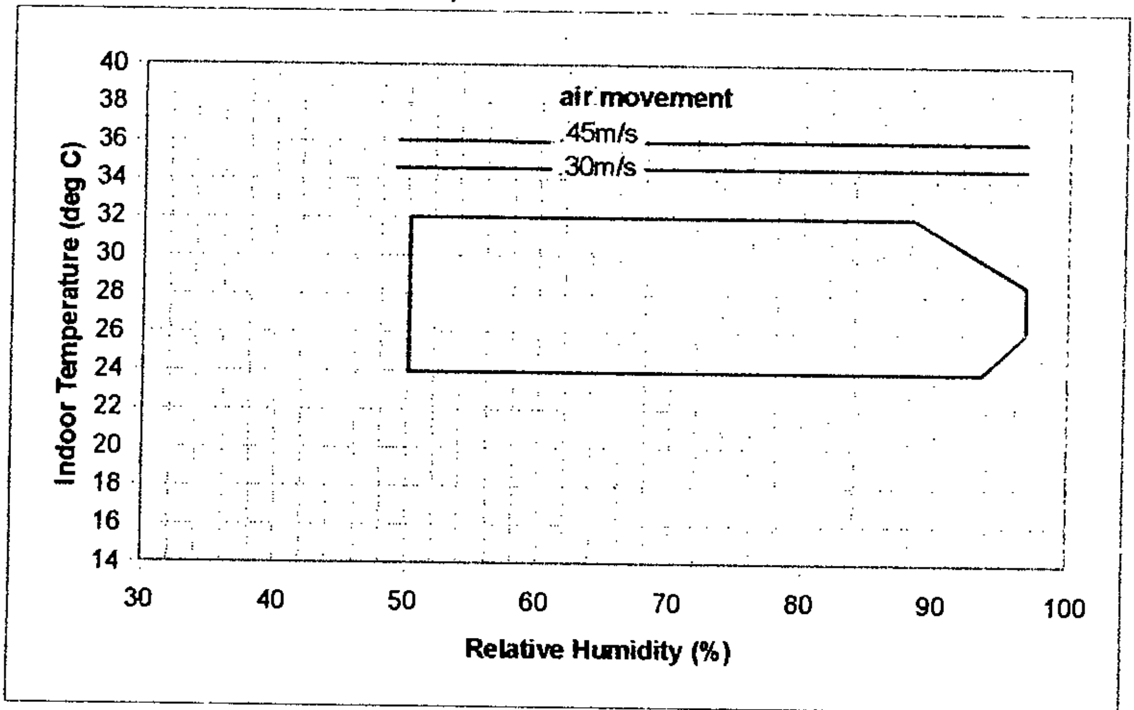

Figure 3.6 Summer comfort zone for Bangladesh (after Mallick, 1994)

Little or slow air movement up to 0.15 m/s makes very little difference to comfort temperatures. The mean comfort temperature for this range is 28.9 °C. For higher velocities of 0.3 m/s to 0.45 m/s the upper and lower limits of comfort temperature increase between 2-3 °K and mean comfort temperature increases to 31.2 °C.

Summer comfort zone for Bangladesh is derived from the above findings, which taken into account the climatic features like air temperature, relative humidity and air movement. The lower and upper limit of comfort temperature is 24 °C and 32 °C while humidity ranges between 50% and 95% in a condition with no air movement. The regime of comfort temperature increases (higher limit) with the introduction of airflow. People feel comfortable above 34 °C with the introduction of air flow at the rate of 0.30 m/s. Tolerance temperature can further increase to near 36 °C with air flow at the rate of 0.45 m/s. The summer comfort zone (Figure 3.6) as developed by Mallick (1994) is adopted as a reference for comfort judgment and evaluation of thermal performance of operable roof insulation in the following chapters like five, six and seven of this research work.

<u>Comfort Vote</u>

Comfort Vote Analysis is based on seven-category thermal sensation scale after Bedford and ASHRAE (Mallick, 1994). It relates to the sensation of comfort as in the Bedford scale (Bedford, 1936) and borrows from the ASHRAE scale (ASHRAE, 1966) for description of outer categories. The middle three categories accommodate the comfort range.

-3	-2	-1	0	1	2	3
Cold	Cool	Comfortable Cool	Comfortable	Comfortable Warm	Warm	Hot
		[	COMFORT ZONE	]		

Regression analysis using comfort votes yielded the best relationship with globe temperature. Following is the formula used for regression line:

$C.V. = T_g \times .29 - 8$ (Mallick 1994)

Where C.V. is the comfort vote, and T_g is globe temperature. When using the equation to calculate the votes for values of globe temperature, fractions were rounded to nearest whole number (e.g..... -1,0,1,2....). This equation is applied in chapter five, six and seven for comparative study of comfort perception for the test room with respect to uninsulated and insulated roof.

3.5 ROOF INSULATION AND COMFORT

The term insulation is normally used for light weight materials such as glass wool, expanded polystyrene, or urea formaldehyde foam, that significantly reduce transfer of heat by conduction due to their very low thermal conductivity. For most insulating materials k is between 0.02 and 0.05 W/mK (Cowan et al, 1983). All insulating materials contain pockets of trapped air (occasionally of other gas). Still air is a very poor conductor; therefore the porous insulating materials are also very poor conductor. So the inclusion of a relatively thin layer on rooftop or in a composite wall reduces its thermal transmittance (U), that is greatly increases its thermal resistance (R).

Because of the porosity and lightweight nature, insulating materials have little or no strength. Usually they need additional support to be installed. Insulation can be added to most buildings after their completion, and this is one of the simplest and cheapest methods of improving thermal efficiency of a building. The insulation is most effective if it is placed on the outside of the building, specifically above roof in tropical countries where horizontal surface receives highest amount of radiation and therefore the fabric of the building is then kept close to the nearly uniform indoor temperature instead of varying with the outdoor temperature and thus possible to achieve thermal comfort. The position of insulation relative to the high thermal capacity mass has a very significant effect on the 'time lag and decrement factor'[1]. With a 100 mm concrete roof slab, the placing of a 40 mm glass wool insulation indicate the following variation (Koenigsberger et al, 1973):

	time lag: (hour)	decrement factor
Under the roof	3.0	0.450
On the top of the roof	11.5	0.046

Insulation on the outside reduces rate of heat flow into the mass. Less heat will enter into the mass or it will take much longer time to 'fill up' the thermal storage capacity while insulation on inside will not affect the 'filling up' process but it will reduce heat emission to the inside space. The term insulation is also used for reflective insulation that reflects radiant heat and effective for reducing radiant heating during day and increasing radiant cooling during night and thereby can significantly improve indoor thermal condition. For thermal comfort in hot climates, aim is not only to store during day as much of the heat that has entered the outer surface as possible, but also to dissipate during night most of this stored heat, so that by the morning the thermal capacity of whole structure becomes empty to absorb the next heat wave; insulation can play a vital role in this context.

3.6 CONCLUSION

The issue of defining the boundaries of acceptable indoor comfort conditions in buildings may have major implications for building design and also may have economic consequences. It is a fact that factors influencing thermal comfort described in this chapter does not necessarily mean they are preferred rather they are result of long-term exposure to such conditions thus become tolerable. There is probably a difference between tolerable and desired conditions and if air conditioned buildings are measures of it, cooler temperatures are desired for. The study is limited to the urban context only, where people are conscious of benefits of devices, which endorse comfort; for rural people the tolerance level may be higher as they are not aware or experience such conditions. Findings of this chapter will help in later chapters to understand the performance of operable roof insulation with respect to comfort issues and help to formulate conclusions and recommendations.

[1] Time lag and decrement factor are two quantities characterizing this periodic heat flow. Time lag (φ) is phase shift that is time difference between T_i max and T_o max. Decrement factor (μ) is the ratio of the maximum outer and inner surface temperature amplitudes taken from the daily mean $$\mu = \frac{T_i \max}{T_o \max}$$ (Koenigsberger et al, 1973)

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CHAPTER FOUR

RADIATIVE COOLING

4.1 INTRODUCTION

Almost two hundreds years ago, Sir Benjamin Thompson (Count von Rumford, 1753-1814), the renowned Massachusetts born British diplomat and Physicist has given a good instinctive description of radiative cooling.

> The excessive cold which is known to reign, in all seasons, on the tops of very high mountains and in the higher regions of atmosphere, and the forests at night which so frequently take place on the surface of the plains below in very clear and still weather in spring and autumn, seem to indicate that frigorific rays arrive continually at the surface of the earth from every part of the heavens.
> May it not be the action of these rays that our planet is cooled continually, and enabled to preserve the same mean temperature for ages, notwithstanding the immense quantities of heat that are generated at its surface, by the continual action of the solar rays?
> If this conjecture should be well founded, we should be led to conclude that the inhabitants of certain hot countries who sleep at night on the tops of their houses, in order to be more cool and comfortable, do wisely in choosing that situation to pass their houses of rest.[1]

Radiative cooling is a common event at the earth surface and the only mechanism by which mother earth can release heat. Considering the impact of sun energy on earth at a rate of about 1.5 X 10^{19} KJ (1.42 X 10^{19} Btu) per day, and over a number of years, the average surface temperature is constant; it is obvious that a similar amount of energy must escape per day. Some of this plentiful energy is reflected back as visible light into the space and a small fraction is converted to chemical energy by the process of photosynthesis. But the largest part heat up the earth's surface, atmosphere, and ocean and is eventually emitted into the space in the form of thermal infrared radiation. It is a very complex process and many paths can be followed by the energy flow originating from the sun and ultimately escaping from the earth into space (Martin 1989).

Any object emits energy by electromagnetic radiation with a spectrum of wavelengths, which depends on its temperature difference. A net radiation heat loss from hotter element will occur if two elements of different temperature face each other. If the colder element can be kept at a fixed temperature, the hotter element will tend to cool down to the same temperature to form an equilibrium state. This phenomenon is the basic principle of radiative cooling process (Goulding 1992) (Givoni 1994). If there was no

[1] This quote is from the closing paragraphs of "An Inquiry Concerning the Nature of heat and The Modes of Its Communication," as first published in *Philosophical Transactions of the Royal Society of London*, 94, (London, 1904) and reprinted in the collected works of Count Rumford, volume 1, pp 323-433, Harvard University Press (Cambridge, MA, 1968), as cited by Marlo Martin in his article *Radiative Cooling*, 1989.

atmosphere, the buildings would 'see' the deep space – an extremely cold resource, the radiative cooling would be ideal, but the sky is an intermediate heat sink[1] with which the external envelope of the building exchanges heat.

In urban areas, high reflectance of vertical surfaces may increase the solar inputs for adjacent buildings but this disadvantage sometimes improve daylight factor in other buildings. But night radiation from vertical surface is small, whereas roof surfaces radiate intensively with less interaction to other buildings (Goulding 1992).

4.2 BASIC PHYSICS OF SKY RADIATION

The fundamental physical principles ensure that each object emitting energy also absorbs it. People radiate and absorb heat at the same time generally at different rates, likewise buildings also emit infrared energy in the form of heat and absorb at different rate from surrounding buildings, trees, clouds and even from the clear sky. Although human beings possess sensitive optical sensors in the visible regions of the spectrum, we have no equivalent way of directly detecting currents in the ocean of infrared radiation in which we are engrossed. At best we feel these effects as warm or cool sensation on the skin, but this nonspecific thermal feeling could equally arise from the convection of warm or cool air (Martin 1989).

4.2.1 Radiation Emitted by Material Objects

All material objects emit heat in the form of infrared radiation where temperature and emissivity of the object regulates the intensity of solar radiation. A high reflective or transmissive material has an emissivity near zero, with infrared emissivity for clean polished metal surface being typically $\varepsilon \approx 0.05$. Most often common materials illustrate high emissivities in the infrared part of the spectrum, including water concrete, glass, paints, woods and vegetation ($\varepsilon \approx 0.9$) (Sellers 1965) (Givoni 1994).

The total amount of radiation emitted by such a substance can be calculated using the formula

$R = \varepsilon_r \sigma T^4$ (Martin 1989) ....(1)

Where σ is the Stefan-Boltzmann constant (5.6686 X 10 $^{-8}$ W/m^2 °K^{-4}), T is the absolute temperature in degree Kelvin, and ε_r is the hemispherical emissivity of the radiator, which can have values between zero and one.

According to Givoni the above formula is perceived as

$R_{emit} = S * E_r * T_r^4$ (Givoni 1994)

Where S is the Stefan-Boltzmann constant, T_r is the absolute temperature of the radiating surface E_r is its emissivity.

In equation (1), the hemispherical emissivity ε_r is taken as a constant but is derived from a general wavelength-dependent optical property of a material $\varepsilon(\lambda)$. The limiting case of blackbody radiation implies that $\varepsilon(\lambda) = 1$ for all wavelength and. A nonspectral "gray" body has a uniform emissivity less than unity over all wavelengths. Emissivity may behave very differently in the infrared part of the spectrum then it does in the visible region. The possibility of making materials having different infrared and visible emissivities has been used in developing selective absorber coating for solar collectors, and for temperature control of satellites and spacecrafts. It has also been investigated for application to radiative cooling systems in buildings (Catalanotti et al., 1975).

The emissivity $\varepsilon(\lambda)$ represent a great deal of physics and is different for each material. The transparency, reflectivity, opacity and color of a body are determined by the form of $\varepsilon(\lambda)$. On the other hand in equation (1) the more general analog for the factor σT^4 expresses a property, which is applicable for all materials interacting with electromagnetic radiation at a wavelength λ. This expression was first derived by Planck and gives the power radiated per solid angle over a unit wavelength interval by a blackbody (Martin 1989):

$B_T(\lambda) = C_1 \lambda^{-5} [\exp(C_2 / \lambda T) - 1]^{-1}$ ....(2)

Where two constant C_1 and C2 have the following values:

$C_1 = 3.7405 \text{ X } 10^{-16}$ W/m^2

$C_2 = 1.43879 \text{ X } 10^4$ μm K

The wavelength λ is expressed in micrometers (1 μm = 10^{-6} m), and the temperature T is in degree Kelvin. At very small and very large wavelength this function approaches zero and reaches a maximum value at a wavelength that depends on the temperature of the emitting body.

The temperature of a radiator especially its relation to ambient air temperature depends on its mass and process of utilization. Therefore its performance is affected by the design factors. For most of the time at night, high mass radiators (e.g. concrete roof or water bags above a metal deck) attain higher temperature than ambient air temperature. Consequently, its radiant heat loss is augmented by convective heat loss to the ambient air, which further increases its total heat dissipation. The temperature of an insulated lightweight radiator (metallic or asbestos cement) is generally below ambient air temperature and the radiant heat loss is counterbalanced by convective heat gain. Thus in determining total energy loss from the radiator (combined radiant loss and convective heat exchange), the type of the radiator plays a very significant role. The temperature of the radiator and its overall, efficiency may also affected by the thermal contact between the radiator and the building that to be cooled (Givoni 1994).

4.2.2 Thermal Infrared Radiation from the Sky

A horizontal radiator approximated by a blackbody at a temperature of 27 °C radiates 460 W/m^2 towards the sky dome. This illustrates a substantial energy flux, which is almost half the incoming solar flux on a day with the sun overhead. Without the presence of atmosphere (as is experienced in the moon), this immense radiative cooling rate could cause to pull down the earth's temperature well below the freezing point soon after the sunset (Martin 1989).

Our atmosphere is composed of mainly nitrogen (78%) and oxygen (21%) with only minute quantities of water vapor, CO_2 and dust. Oxygen and Nitrogen are mostly transparent to infrared part of the spectrum. CO_2 is a very strong emitter and absorber of infrared radiation, which is around 15 μ, comprises only about 0.03% of the atmosphere by volume. The net outgoing radiative flux from a terrestrial object is equal to its emitted flux [equation (1)] minus absorbed incident flux from the atmosphere (Givoni 1994).

Figure 4.1 shows intensity of sky radiation increases with the increase of atmospheric humidity, therefore the net radiative cooling capacity is reduced under high humid condition. Water vapor emits and absorbs radiation at wavelength of 6.6 and 18 μ. As the water vapor

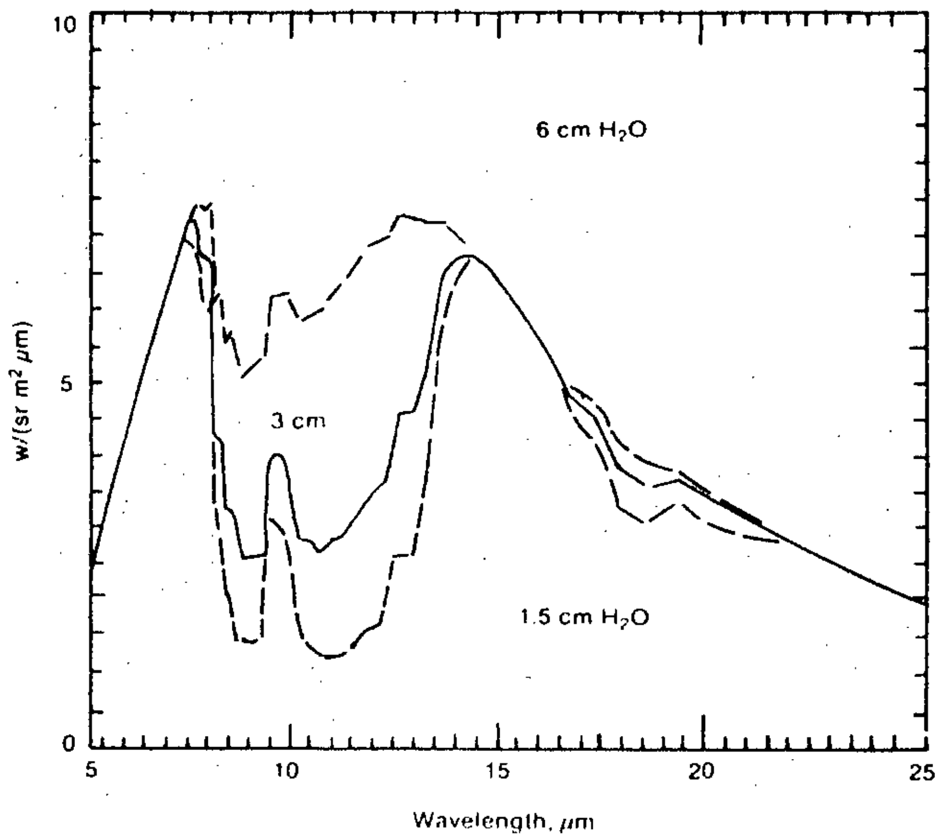

Figure 4.1 Calculated spectral sky radiance for clear mid latitude summer atmospheres containing different amounts of water vapor. The total amount of water vapor in a vertical column is expressed as the height of an equivalent column of the condensed liquid. (Source: Berdahl and Martin 1978)

of the air increases, the corresponding increase of the intensity of atmospheric back radiation is observed, which results in strong total atmospheric back radiation towards the earth. Clouds play another dominant role in the net cooling rate. Clouds, especially low clouds emit radiation through the whole long-wave spectrum, thus under an overcast sky the phenomenon of sky window practically disappears and atmospheric radiation reaches its maximum. Under clear sky condition and low humidity, the atmospheric radiation is in distinct wavelength bands – the 3 to 8 μ and the 8 to 13 μ bands. Between 13 to 20 μ the atmospheric back radiation (radiation emitted by the atmosphere downward towards the earth) is weak and 8 to 13 μ bands is designated as "atmospheric window" greatly affects the rate of radiant heat transfer from terrestrial objects. (Martin 1989) (Givoni 1994).

4.2.3 Heat Balance for a Horizontal Exposed Radiator

When the sky is clear, the radiative sky temperature in the region of zenith is lower than that of Horizon. Therefore, at low angles, a horizontal radiator picks up less radiation, which is emitted by the atmosphere and attains a good radiative contact with the coolest part of the sky dome. This type of orientation is optimal for the emitter element and is usually preferred to using tilted emitters. The net radiative heat flux from such a (blackbody) surface is simply described by the following equation in the absence of convective heat gain:

$$R_{net} = 4\varepsilon_r \sigma T^3{}_{air}(\Delta T_{sky} - \Delta T_{rad}) \qquad (3a)$$

or

$$R_{net} = 4\varepsilon_r \sigma T^3{}_{air}(T_{rad} - T_{sky}) \qquad (3b)$$

This formulation is useful in calculating the energy incident on a black or gray surface if the sky temperature or the sky depression is known. The factor $4\varepsilon_r \sigma T^3{}_{air}$ appearing in these expressions is the equivalent linearized radiative heat transfer coefficient h_r ((Martin 1989).

In a real system heat gained by convection from the ambient air can take on the same orders of magnitude similar to net radiative loss. Clark and Berdahl (1980) suggested using an equation for the turbulent heat transfer coefficient h_c based on the relationship for airflow over a rough horizontal surface:

$$h_c = [0.054\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}]k / L \qquad (4)$$

Where k is the thermal capacity of air, Re is the Reynold's number, Pr is the Prandtl number, and L is the characteristic length (here 20 ft is used). They find that this equation can be linearized with respect to the free stream air velocity to give

$$h_c = (0.5 + 0.3v) Btu.hr^{-1} ft^{-2^0} F^{-1} \qquad (5)$$

in which v is the air speed in mph. This equation predicts values for h_c that are too large when v < 3 mph, due to the onset of laminar flow. The value of $h_c = 0.139$ Btu hr^{-1} ft^{-2} $°F^{-1}$ should be used under such condition (Clark and Berdahl 1980).

Based on further detailed investigation on heat transfer measurement carried by the same group of investigators recommended that the air speed in convection calculation be 0.1 times the meteorological value (Clark et al 1983b). A flat roof surface located on top of a building with parapet wall (as in their experiment) will experience a substantially different flow pattern from that of a flow plate suspended in an air stream, because of the flow separation occurring at the top edge of the wall. This shielding effect is helpful for the performance of a radiative cooling system whenever the night air is warmer than the radiator, since the heat gain by convection is reduced.

4.2.4 Conductive Heat Exchange with Ambient Air

Radiant cooling process is always associated with convective component of heat exchange. The convective exchange is a function of convective coefficient, which depends on the wind speed near the exposed long-wave radiators. It is proportional to the temperature difference between the radiator and the ambient air. The convective coefficient is very difficult to estimate accurately. The factors on which it is depended is the wind speed next to the radiating surface and the type of airflow, whether it is laminar or turbulent. Practically any value assumed for air speed should be considered only as rough estimate, because the wind speed direction that comes through meteorological stations may not match 100 % for a particular site for local factors and deviations (e.g. parapet wall). Thus, there is no way to know accurately the nature and speed of the wind next to the radiating surface (Givoni 1994).

In radiating cooling system, where it can be expected that for most of the period at night, the radiating surface will be above ambient air temperature (e.g. heavy concrete roof); cooling rate is increased by high wind speed as the wind speed increases convective heat loss. On the contrary, in those radiant cooling system, where the radiant temperature is planned to be below the temperature of ambient air (e.g. lightweight air-cooled radiator), infrared windscreens can be applied to minimize convective heat gain from the warmer air (Givoni 1994).

The general formula for convective heat exchange between the radiator and the ambient air is:

$$Q_c = h_c * (T_r - T_a) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where T_r = absolute temperature of radiating surface, h_c = convective coefficient, T_a = ambient temperature.

Various authors have suggested different formula to evaluate this coefficient (Duffie and Beckmann 1974), (Hansa and Yellott 1978), (Clark and Berdahl 1981), (Mostrel and Givoni 1982). Based on the analysis of various experimental data involving exposed and wind screen radiators has suggested formula:

For an exposed radiator

$$h_c = 0.6 + 3.5(V)^{0.5} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

For a radiator covered by a single Polyethylene layer

$$h_c = 0.5 + 1.2(V)^{0.5} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

For a double covered radiator

$$h_c = 0.3 + 0.8(V)^{0.5} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

When a radiator is wind-screened by polyethylene layers, both the absorption of sky radiation (R_{abs}) and the emittance of radiation to the sky (R_{emit}) are modified by the long wave transmission of the wind-screens, trans, and the emissivity of the radiator E_r (Givoni 1994):

$$R_{abs} = E_r * trans * R_{sky} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$$R_{emit} = E_r * trans * \sigma * (T_r)^4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Where σ is the Stefan-Boltzmann constant.

The values of trans are assumed to be 70% for a single layer and 60% for a double layer. The net radiant loss can thus be evaluated under different cloudiness by the following formula (Mostrel and Givoni 1982):

$$R_{net} = C_n * trans * E_r * 0.554 * (T_r - T_{sky}) \dots\dots\dots\dots\dots\dots (12)$$

Where C_n is the (Clark and Allen 1978) formula for the cloudiness coefficient:

$C_n = 1 - 0.056 * n$ (n is the cloud cover index).

By balancing the net radiant loss and the convective gain ($R_{net} = Q_c$) the following linearized formula predicts the stagnation temperatures (T_{stag}) of a metallic radiator as a function of the air and sky temperatures, cloudiness and the wind- screen transmittance (Mostrel and Givoni 1982):

$$T_{stag} = \frac{0.544 * C_n * trans * E_r * T_{clearsky} + h_c * T_a}{0.544 * C_n * trans * E_r + h_c} \dots\dots\dots\dots\dots\dots (13)$$

4.2.5 Infrared Emissivity for Clear and Cloudy Skies

Clear sky has been recognized as a source of radiative cooling from long, which is generally well understood in terms of the vibrational-rotational emission band of atmospheric gas modules (Kondratyev 1965), (Wolfe et al 1978).

Numerous attempts were made to correlate a more limited set of experimental measurements with commonly available weather parameters since Angstrom's empirical equation was first introduced in 1916 (Sellers 1965). More recent measurements of clear sky emissivity can be obtained equation (Berdahl et al 1984)

$$\varepsilon_{clear} = 0.711 + 0.56(T_{dp}/100) + 0.73(T_{dp}/100)^2 \dots\dots\dots\dots\dots\dots (14)$$

where T_{dp} is the dew point temperature expressed in degree Celsius. This equation is obtained from monthly averaged clear sky measurements. If instantaneous emissivities are to be estimated, a small diurnal variation term should be added to the equation (Berdahl et al 1984)

$$\Delta\varepsilon_d = 0.013\cos\left\{\frac{2\pi t}{24}\right\} \quad \text{.............................}(15)$$

where t is the hour. A small pressure correction is set up to correct for the observer' elevation (Staley et al 1972)

$\Delta\varepsilon_p = 0.00012(P-1000)$. P is expressed in millibars.

On the other hand infrared emission from cloud is stronger than that from the clear sky, as cloud droplets closely approximate blackbody radiators. The strongest are dense low strata formation consisting high cloud base temperatures. High thin cirrus clouds contribute only slightly to the atmospheric radiation, which is downward directed. In radiative cooling applications, the methods for calculating the total downward-directed sky radiation is preferred, in view of the fact that net radiation strongly depends on the temperature and emissivity of the radiator surface which is being used (Martin 1989).

The quantity of infrared radiation received from clouds depends on their temperature and the fraction of the sky dome filled by them. Cloud based temperature generally reduce with height, with the exception where an atmospheric inversion layer exists. A method to estimate the total sky emissivity has been proposed by Martin and Berdahl (Martin et al 1984a), which is based on, observed cloud amounts n_i for clouds at various heights. The cloud emissivity $\varepsilon_{c,i}$ is assumed to be 1.0 for opaque and 0.4 for the cirrus clouds. The total sky emissivity can be expressed as

$$\varepsilon = \varepsilon_o + (1-\varepsilon_o)\sum n_i \varepsilon_{c,i} \Gamma(T_c) \quad \text{.............................}(16)$$

here ε_o is the calculated clear sky emissivity, T_c is the cloud based temperature, the factor $\Gamma(T_c)$ contains the cloud temperature dependence, which can be estimated if the height of the cloud is lower, based on typical lapse rates.

4.3 RADIATIVE COOLING PROCESS

Emission of long wave radiation is a continuous process, which takes place day and night (24 hour cycle). But during daytime, surfaces radiating long wave radiation are subjected to solar radiation, which eventually prevail over thc cooling effect produced by emission of long wave radiation. For that matter, cooling can only be obtained during nighttime; therefore radiant cooling is often recognized as 'nocturnal radiation'.

The long wave radiation emitted by the building is continuous over the range of 5 to 30 μ (micron) with peak radiation at about 10 *u* (Gray-body radiation). The spectrum of radiation depends on moisture content of the air and particularly on the condition of cloud. The net radiant heat loss from a radiator placed on a rooftop of a building is the balance between the energy flux that is emission of long wave radiation from the radiator surface and at the same time absorption of incoming atmospheric radiation by the radiator. In calculating the net radiant heat loss, two components are important, the 'effective sky temperature' the 'sky emissivity'. Givoni defines them as follows

> "The effective sky temperature is defined as the temperature of a black body that radiates towards the ground with a continuous spectrum at the same energy flux as the measured atmospheric radiation under given climatic conditions, The sky emissivity assumes that the same radiant flux is emitted from an atmosphere with the same temperature as that of the air near the ground but with a emissivity". (Givoni 1994)

Not all the net radiant heat loss is utilized as cooling potential for building. Nocturnal radiator can gain heat by convection if its temperature is below the temperature of ambient air. Some cold energy is lost during the process of transfer from radiator to the building and the effective cooling (of building) is less than radiant net loss. Then again when the temperature of the radiator is above the temperature of ambient air, the effective radiant cooling takes place, moreover convection to the ambient air also becomes a cooling resource.

According to Givoni (Givoni 1994) there are three basic types of nocturnal radiators that utilize the physical process of radiant heat loss as cooling resource of buildings. They are as follows

a) A high mass roof with operable insulation, where insulation panels expose the roof mass to the sky during night time and close the roof mass during day, serving as a combined radiator/cold storage element.

b) A lightweight, usually metallic radiator that cools ambient air below initial temperature and then directed into the building to provide instantaneous cooling during night.

c) Unglazed water type solar collector, where cooled water is circulated in pipes embedded within the concrete roof or wall and thus making a heat sink for absorbing heat into the building during day time.

More detailed discussion of the implementation details of these options is presented below.

4.3.1 High-Mass Roofs with Operable Insulation

If a roof of high thermal mass is exposed to the sky during the night, it is cooled down by long-wave radiation, and frequently as well by convection to the cooler outdoor night air, making the roof mass into a cold energy storage. As soon as the cooled mass that is insulated from the ambient air during the daytime is thermally coupled with the cooled mass, it absorbs heat from the space below. For that matter, to work as a cooling system, the roof has to be insulated from the sun and hotter ambient air during daytime hours resulting in minimization of heat gain from the outdoor environment. Therefore, the system has to incorporate movable or retractable insulation above the roof, which exposes it during the night and insulates it during the daytime. A high mass roof with the provision of operable insulation can perform as an efficient combined radiator/storage cooling element. A high-mass structural dense concrete roof, when equipped with operable insulation, is a simple implementation of the concept. (Figure 4.2). The thermal mass cools down at night at a lower rate than the ambient air. During some or most of the night,

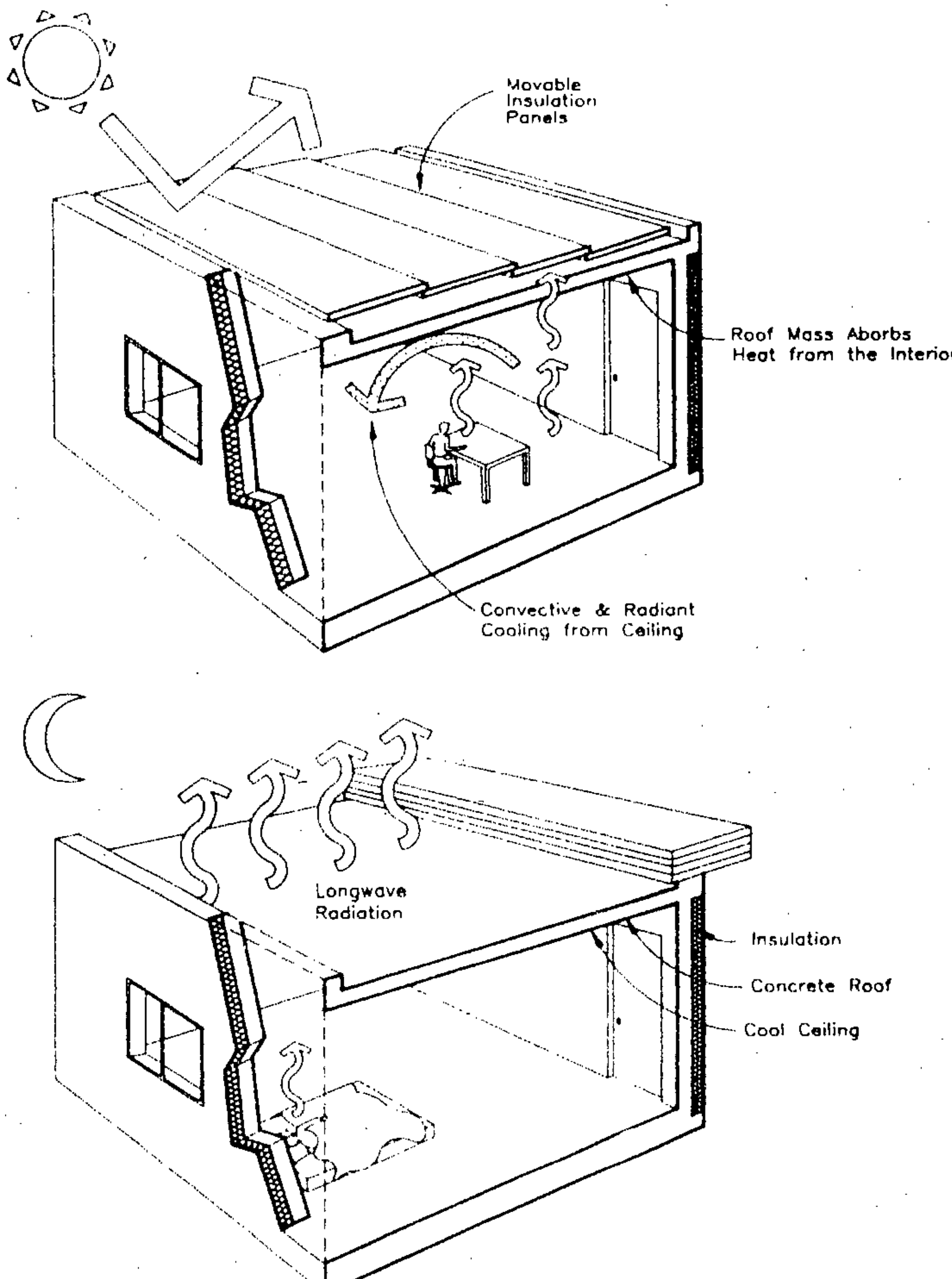

Figure 4.2 Concrete Roof with Operable Roof Insulation as a nocturnal radiator. (Source: Givoni 1994)

its surface has a higher temperature than the air. Consequently in addition to radiant heat loss, it is also cooled down by convection. So a higher wind speed increases the cooling rate of a high mass roof. With a suitable design it is possible to cool the storage mass to a temperature below the daily average of the outdoor temperature. (Givoni 1994)

4.3.2 Lightweight Nocturnal Radiators

A thin plate above the roof and insulated underneath, does not store much solar energy nor does it gain heat from the space below the roof. Temperature of such lightweight radiator is lowered by emission of long wave radiation below the ambient air level. Consequently convective heat gain from the air counteracts the radiant heat loss until the equilibrium is established between heat gain and loss, and the radiator's temperature is stabilized at some level below the ambient air. As wind speed increases the temperature of the emitting surface, the convective heat gain depends on it near the emitting surface.

The net heat loss at the external surface of the roof with conventional insulation cannot be utilized directly for cooling the building, due to thermal resistance of the roof. To utilize cooling effect of nocturnal radiation, the cold energy produced by the radiating surface should be transferred into the interior of the building. At night, when ambient air is sucked by a fan through a "channel" between cold radiator and insulation layer beneath, it is cooled by the radiator (convective cooling). To cool the interior mass and the inhabitants in the space, the cooled air can be directed into the space. Nocturnal Radiative cooling thus can be stored in the interior structural mass of the building, with the cooled mass acting as a heat sink during the following day. Alternatively, the cold energy can be stored in a specialized mass (for example in a gravel bed under the building). Figure 4.3 illustrates a building with a metallic nocturnal radiator and cold storage in the interior structural mass of the building as daytime utilization of radiant cooling is possible only in high mass building or in low mass building with supplemental specialized storage mass. (Givoni 1994)

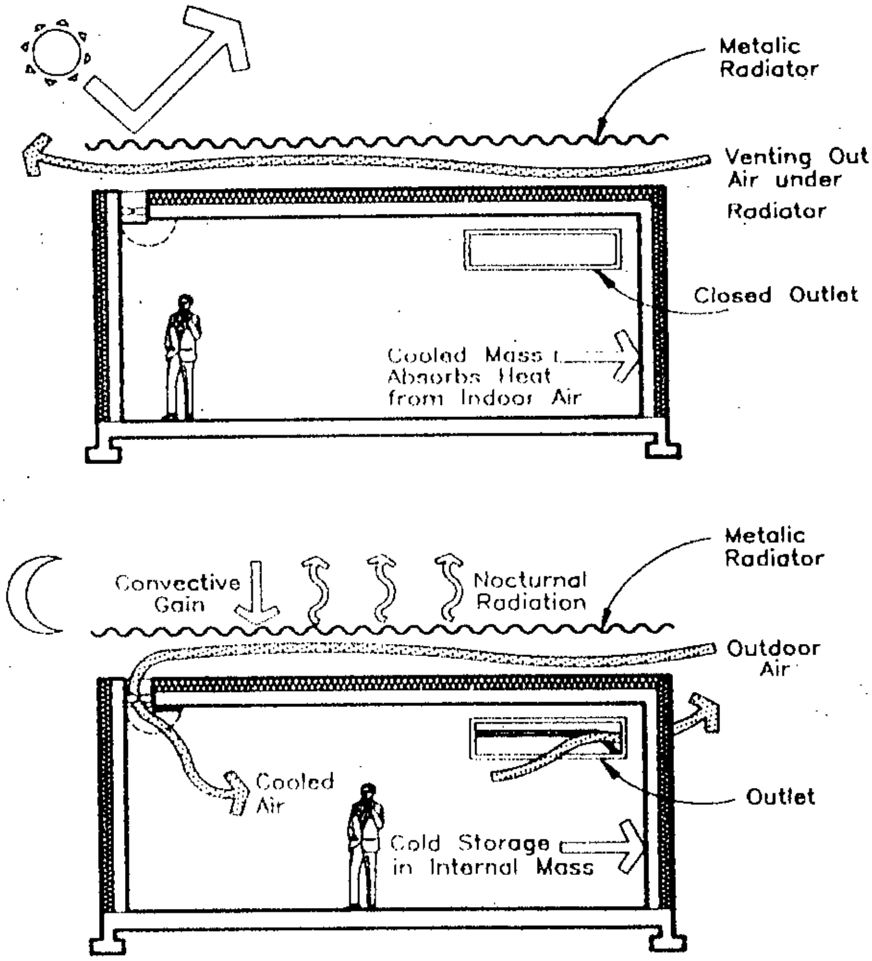

Figure 4.3 The Cooling process of Lighiweight nocturnal radiator. (Source Givoni 1994)

4.3.3 Unglazed Solar Collectors as Nocturnal Radiators

It is possible to install unglazed solar collectors over the roof and to circulate water through them at night during summer. One of the following ways, the cooled water can be utilized:

i) The cooled water can be circulated through the roof material- the concrete. In this way roofs serves as thermal storage and ceiling as a radiant cooling panel above the space to be cooled (Figure 4.4).

ii) The cooled water can be circulated through a water pond over the roof and below the collectors (Etzion 1989). The pond then serves as the main thermal element.

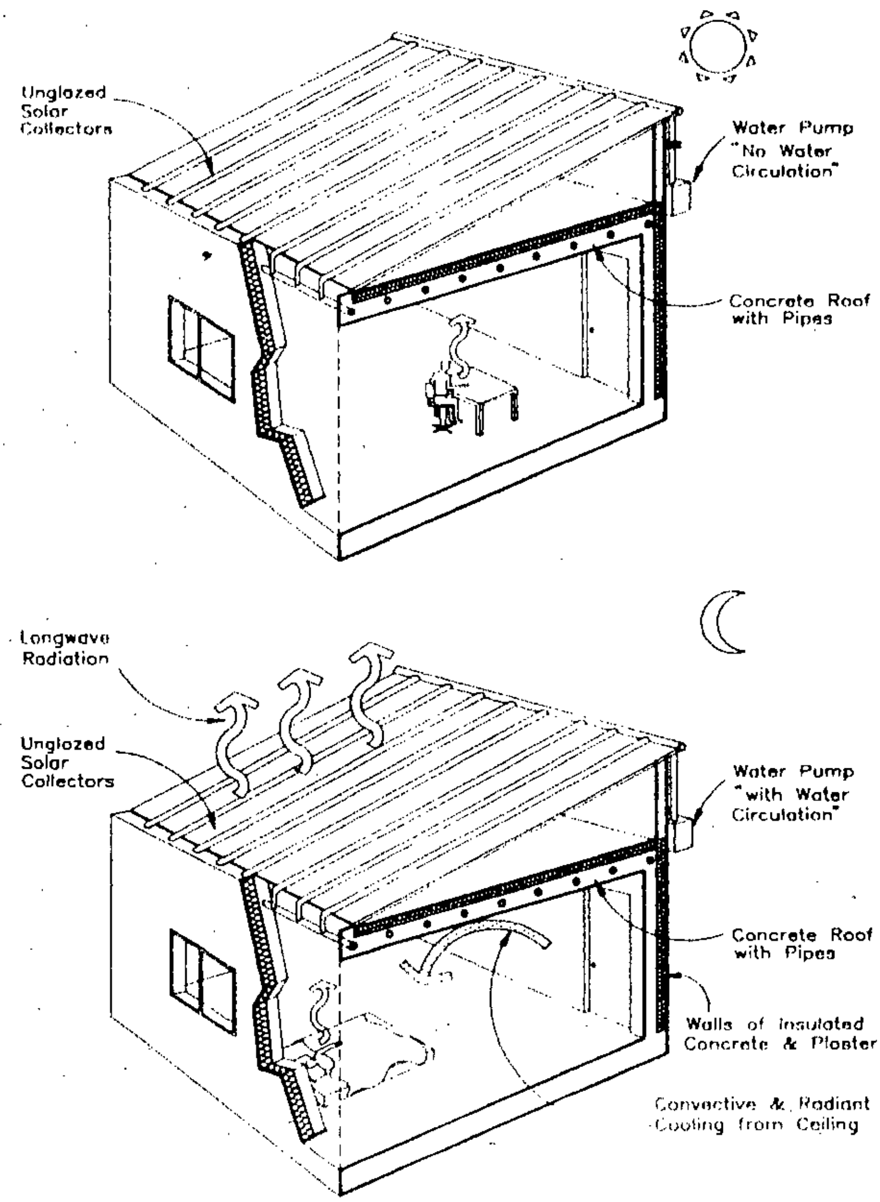

Figure 4.4 Unglazed solar collector functioning as a nocturnal radiator. (Source: Givoni 1994)

4.4 CONCEPTS AND SYSTEMS OF RADIATIVE COOLING

a) The "Skytherm" Systems and its Variants

The "Skytherm" is the first roof system utilizing nocturnal radiation for cooling a building and only commercially available developed by Hay (1978). In this system the structural roof consists of a horizontal metal deck where thermal mass is provided by large plastic bags, filled with water and placed above the metal. Horizontal insulating panels, which are moved by a motor, insulate the water bags during the daytime and expose them to the sky at night, when they slide aside and stack over a porch or garage. The metal ceiling serves as a cooling panel for the space below. Figure 4.5 shows a scheme of the Skytherm System. The process is reversed during the winter and the system acts as a passive solar heating system. This system offers an efficient cooling mechanism due to the good thermal coupling between walls and the indoor space and the high heat capacity of water. Several researchers have developed and tested various modifications of Hay's original design with a view to overcome some technical difficulties that were experienced with the horizontal panels. The following are the buildings with the Skytherm System which have been tested for their cooling performance:

- The Phoenix Prototype
- The Atascadero Building
- The New Mexico State University Building
- A building with the modified roof pond in Pala

<u>The Prototype in Phoenix, Arizona</u>

The Phoenix prototype was a 10 by 12 feet room with vermiculite filled concrete block walls and insulated by 1.5-inch rigid polyurethane. The roof was built of corrugated steel sheets. A polyethylene liner formed three water-proved ponds. The insulation over the pond consisted of 1.5 inch thick polyurethane panels, manually operable by nylon clothlines with help of pulleys. The panels were stacked atop the carport when retracted. In summer, the pond was exposed during the night and insulated during the day. In winter the process was reversed.

As reported by Marlett et al (1984), the water was exposed on the roof (that is, it was not contained in bags). Therefore the cooling was mainly by evaporation, not by radiation. The interior temperature was maintained in a range between 68 and 82 ^{0}F. During the summer months, with maximum temperatures upto 110 ^{0}F and high humidity, a fan-coil unit circulated the ponds water through the unit.

The House in Alascadero, California

The Alascadero house built and originally owned by Hay, was the first building of full size, which utilized the Skytherm system. It is a single story building with three bed room and made of hollow lightweight concrete and insulated wood –frame walls. The structural roof consists of corrugated steel deck plates. Thermal storage is in large water filled plastic bags. Insulating panels are movable by the help of a motor and stacked over the carport when retracted, cover the water bags.

The performance of this house was monitored and evaluated by the California Polytechnic State University (1975). Most of the Marlett report (Marltt et al 1984) deals with the heating performance of the building in winter, but some information is also provided on the summer cooling performance. The interior temperature was kept within the range from 20 to 23 ^{0}C throughout the summer by the roof pond. In evaluating the performance, it should be noted that in summer the outdoor average temperature in Alascadero is within the comfort range. So in practice just the thermal mass of the water and the walls, even if insulated by fixed insulation, could maintain a comfortable indoor temperature for most of the time under the climatic condition of the site.

The New Mexico State University Building (NMSU), Las Cruces

The building built and tested by the NMSU is a single story three-bedroom house in which walls are of 15 cm thick load bearing R.C.C. and the floor too. Las Cruces has a more severe summer climate than Alascadero; thus, it could provide more realistic conditions for evaluating the cooling performance of the skytherm system.
The Marlett (1984) report indicates excellent cooling performance of this building.

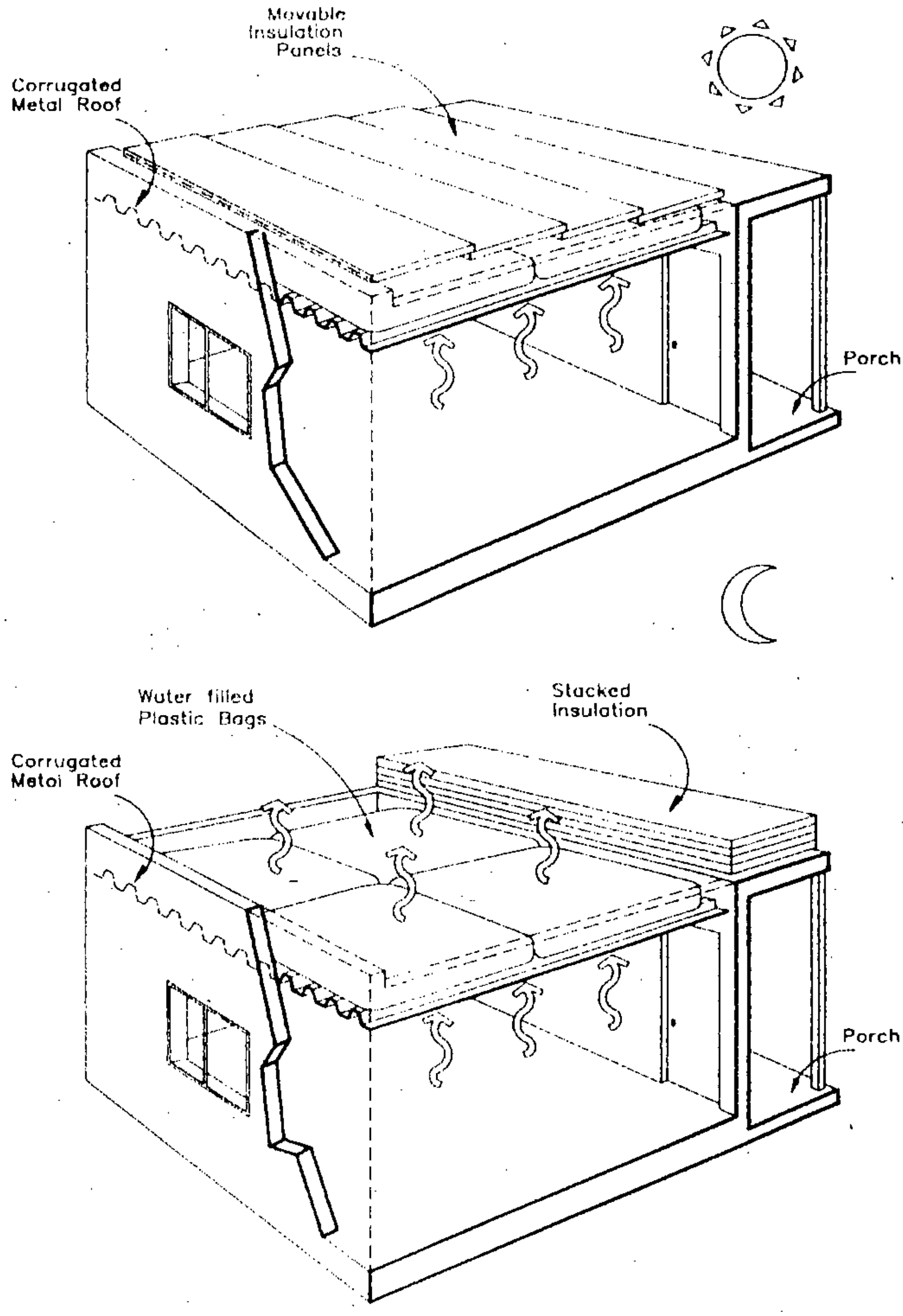

Figure 4.5 The Skytherm System. (Source Givoni 1994)

The Pala Roof Pond Variant

The Pala passive solar facility, owned by the San Diego Gas and Electric Company has eight test buildings but out of them only two are related to radiant cooling. Each building is equally divided into two rooms by an internal wall and has a floor area of 25 m^2. The ceiling height is 2.4 m. The roof pond building has a flat steel deck structural roof that supports large water filled plastic bags similar to skytherm system. But the operable insulation panels were of different in design. Instead if panels stacking horizontally, they mover accordion-style and hinged together with standard door hinges. They slide on tracks mounted vertically on the top of the parapet of the roof (Figure 4.6).
The indoor temperature of the roof-pond building was that of the conventional throughout that time, especially with respect to the maxima. In July the maximum temperatures of the roof pond buildings were about 6 ^{0}C below the maxima of the conventional buildings and in October the difference was about 9 ^{0}C. These figures indicate a very important point regarding the interaction between building design and passive cooling, appropriate for a given climate. The relationship between outdoor and indoor temperatures was rather similar in July and in October. Solar gain through the small-unshaded windows and solar absorption in the building's envelope have raised the indoor temperatures so that in July the average temperatures of both buildings was above the outdoor average. The temperature of the conventional building was almost always above the outdoor level and its maximum was about the same as outdoors. But the temperature of the roof-pond building was too high relative to the outdoor situations, indicating that the total direct and indirect solar heat gain was more than the cooling provided by the roof pond, although its area was the same as the floor area (Givoni 1994).

b) **Concrete Roof as Nocturnal Radiators**

In many countries, roofs are generally constructed as flat (horizontal) and has become a standard practice unless to meet very specific requirements. If such roofs could be equipped with one form or another of operable insulation that could cover the roof during the daytime and expose it (roof) to the sky during the nighttime, then the roofs would function as effective nocturnal radiators.

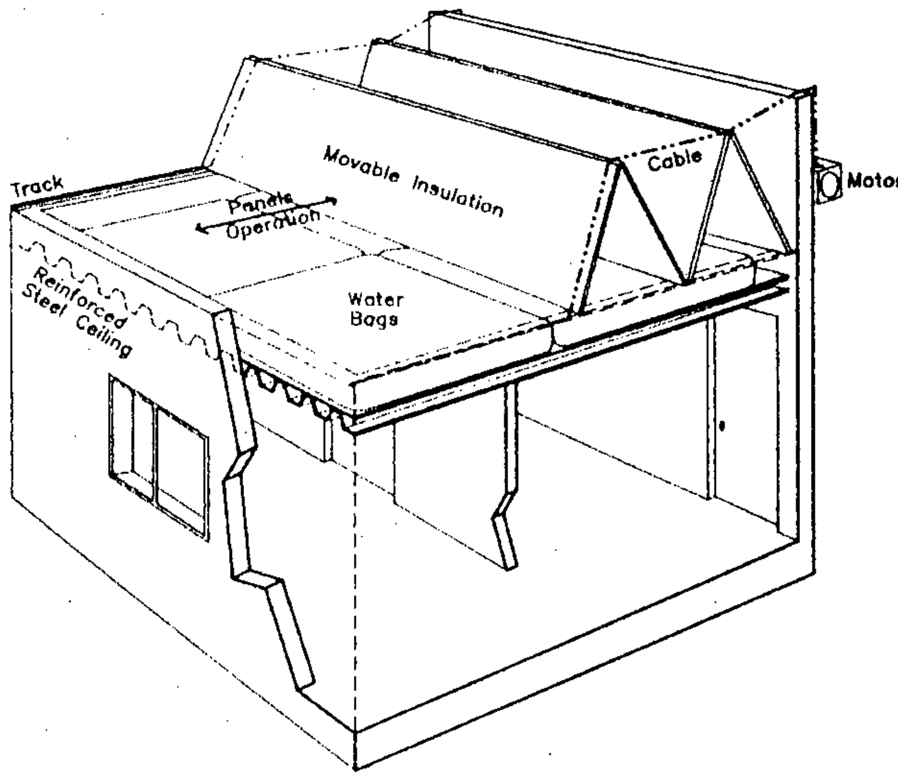

Figure 4.6 The Pala version of the Skytherm system

The performance of this concept was tested by Givoni (1981) at the Institute for Desert Research of Ben Gurion University in Sede Boqer, Israel, with small lightweight test cells measuring 55x55x50 cm with walls of Polystyrene sandwiched between plywood sheets with a 10 cm thick concrete roof. A 5 cm thick Polystyrene plate was used to cover the roof during daytime and during the nighttime it was exposed. The experimental cell was compared with a "control" of a similar cell with a super insulated roof.

The average results are summarized in the following table:

	Minimum	Maximum	Average
Outdoor Temperature	14.5	27.0	20.7
Indoor-Experimental	14.0	21.3	17.2
Roof Surface (Exp)	12.0	19.3	15.2
Indoor-Control	19.4	25.6	22.5

Thus it is evident from the above table that the concrete nocturnal radiator has lowered the indoor maximum temperature by 5.7 ^{0}C (46% of the outdoor range) and the average by 4.3 and 5.4 ^{0}C respectively below the temperature of a similar cell with well-insulated roof.

Later this concept was tested by Etzion and Dover (1989) at the same institute with larger test cells measuring 136x136x108 cm with walls made of 6 cm polystyrene inserted between two sheets of plywood, painted white. The roof was constructed of 10 cm thick concrete with a movable insulation panel of 10 cm polystyrene. The roof insulation was installed during daytime and removed during nighttime. The relative heat gain through the walls was increased due to higher height of floor area ratio while the better daytime insulation lowered the heat gain through the roof during daytime relative to the smaller cells of Givoni's (1981) experiment. Figure 4.7 shows diurnal patterns of the outdoor and indoor temperatures during a sequence of four days in July 1987. With averages of the outdoor maximum air temperature of 38, minimum of 19 and average of 29 ^{0}C, the respective indoor air temperatures were maximum 29.5, minimum 17.5 and average 24 ^{0}C. So, the concrete nocturnal radiator with daytime insulation lowered the indoor maximum temperature by 8.5 ^{0}C (45% of outdoor range) and indoor average by 5 ^{0}C below the outdoors' respective level. Figure 4.8 illustrates the performance of a test cell with concrete nocturnal radiator over a period of seven days in September 1987. Again, the indoor temperatures were maintained well below the outdoor and the indoor maximum was lowered below the outdoors' level by about 50% of the outdoor range.

It is interesting to note that in above three cases the indoor maximum temperatures were lowered below the outdoors' maximum by a similar fraction of the outdoors' range (45-50%).

c) Metallic Lightweight Radiators

Operable insulations are necessary if high-mass roofs are used as nocturnal radiator, which are of course technically a problematic item. However, instead of cooling the mass of the storage medium itself, it is doable to cool a specialized long-wave radiator, placed over an insulated roof, to temperatures below those attainable when the storage mass is cooled directly.

The radiator should preferably be a metallic one to minimize thermal resistance between the upper surface (where radiant loss takes place) and lower surface (where cooling of flowing air occurs). To prevent heat flow to the radiator from the roof below, it should be insulated underneath with a cavity.

The net radiant heat loss and the heat gain by the convection from the ambient air are balanced when radiant heat loss from a lightweight radiator is not utilized by airflow under the radiator (stagnation condition). This balance makes a temperature depression of the Radiative surface below the ambient air when heat loss by radiation equals heat gain by convection. Under these conditions the temperature difference between ambient air and Radiative surface is highest (if stable condition in wind speed and cloudiness are assumed) (Givoni 1994).

The temperature thus attained is termed as 'Stagnation Temperature T_{rs}' and example of measuring the temperature of Lightweight metallic radiators by Givoni in two climatic regions of Israel:

> The Haifa Study: Effect of Radiator Color: In Haifa (Givoni 1976) the stagnation temperature was measured with exposed radiators made of asbestos cement sheet without a polyethylene windscreen. Lot of dew formed over the radiators in almost every night during the experimentation. In clear nights, in spite of heat gain from condensation of the dew, the surface temperature dropped significantly below the ambient air. Figure 4.9 illustrates patterns of stagnation temperature of gray and white horizontal panels of insulated asbestos cement measured in Haifa in midsummer of 1964 for three clear days (Givoni 1994).

It can be seen in both cases (even though the climate is humid) that the nighttime temperatures have dropped by about 5 to 6 °K below the ambient air. The figure indicates two points of practical significance:

1. As long as the sky is clear, radiant cooling has an effective potential even in humid regions.
2. The color of the radiators does not affect its performance for nocturnal radiant cooling but during daytime it would result in very different temperatures.

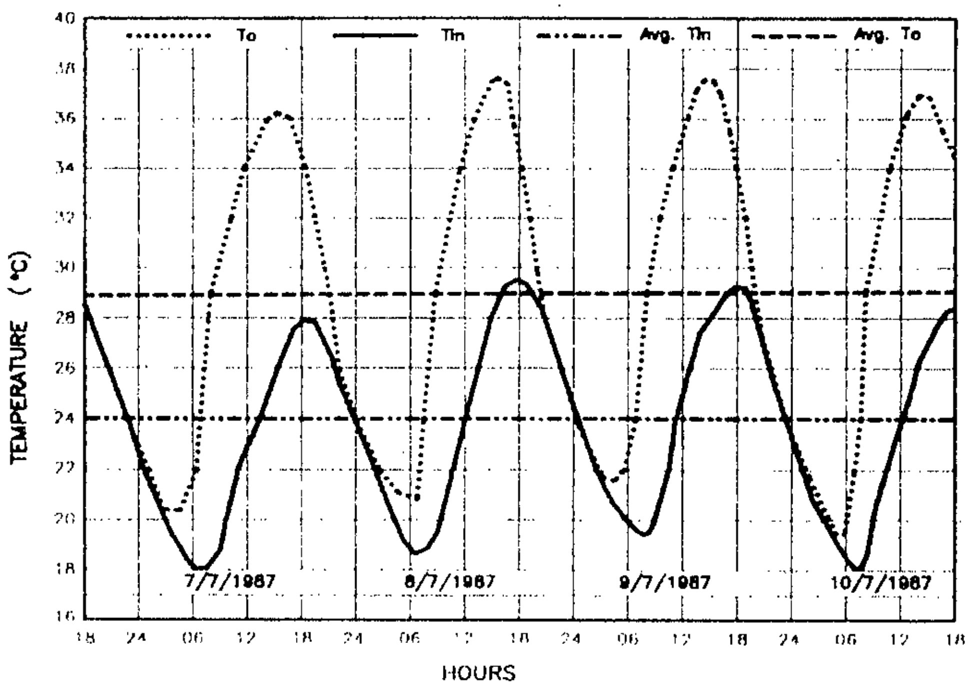

Figure 4.7 The cooling performance of concrete roof with operable insulation, serving as a nocturnal radiator during four days in July 1987. (after Etzion and Dover 1989)

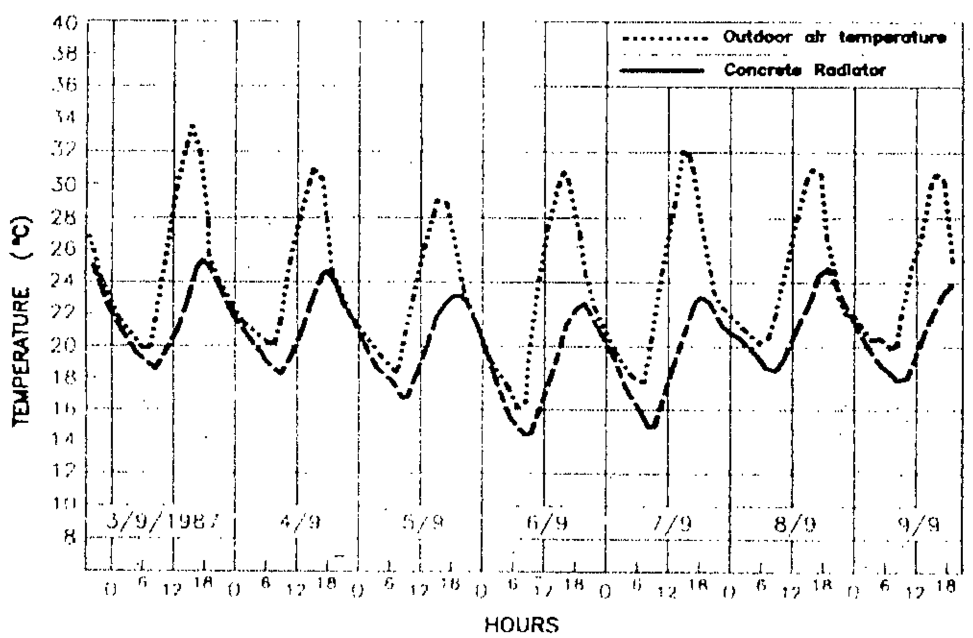

Figure 4.8 The cooling performance of concrete roof with operable insulation, serving as a nocturnal radiator during seven days in September 1987. (after Etzion and Dover 1989)

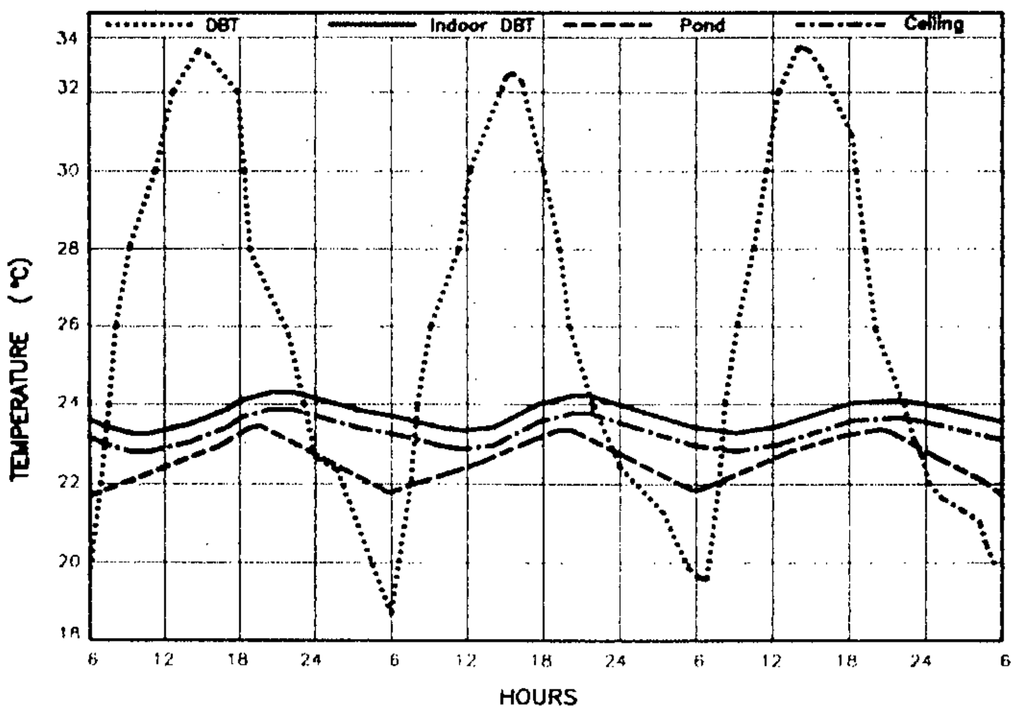

Figure 4.9 Surface Temperatures of gray and white lightweight radiators. (source Givoni 1994)

Consequently, an exposed dark radiator (over well insulated roof) can be used in winter during daytime as a low cost low efficiency air heating and in summer as a radiant cooling system. In both cases, the interior structural mass will provide thermal storage.

The Sede Boqer Study: Effect of Polyethylene Wind Screens: In Sede Boqer, which is in arid climate, the experiment was done to examine the effect of polyethylene windscreens on the stagnation temperature of metallic radiators. The temperature drop under stagnation conditions was about 5 to 8 °C for exposed radiators and incase of screen radiators the drop was about 9 to 10 °C. However, when dew was precipitated over the polyethylene the effect of the windscreen practically disappeared. The experiment also indicated that there is no significant difference between single and double layers of polyethylene.

Effect of Radiator's Utilization on its Temperature: When outdoor air flows under the radiator while insulation restricts heat flow to the air stream from the roof below, its temperature drops towards stagnation level. The potential cooling of air is always lower than the depression of stagnation temperature.

The heat transfer from flowing air to the radiator is increased by higher airspeed under the radiator and higher flow rates per unit area of the radiator. Thus more heat is actually dissipated by the radiant loss and further improvement of thermal condition can be achieved by installing an electrical fan for moving the air.

d) Screened Asbestos-Cement Sheets as Nocturnal Radiators

Givoni and Hoffman (1970) have studied the possibility of using corrugated asbestos cement sheets, which are a very common roofing material in many developing countries. They have measured indoor temperatures of a room, which is roofed by asbestos-cement sheet and covered with polyethylene windscreen functioning as a nocturnal radiator. The research took place in the hot desert town of 'Eilat' in Israel. A 6x3 m room was build specifically for the study. The walls and roof was constructed with 20 cm concrete and insulated externally by 5 cm polystyrene and white corrugated asbestos cement sheet. The roof sloped down from a height of 2.8 m at the north wall to a height of 2.0 m at south wall. It was shorter than the length of the room by 1 m in north and south orientation, creating a gap in which hinged operable insulation panels were installed. A polyethylene sheet was stretched 10 cm above the asbestos-cement so that indoor air could exit through northern gap ay night when roof panels were open, thereafter flowing down the sloped roof by gravity between polyethylene and asbestos sheets these air were cooled down by radiant loss to the sky and reentered the room through the open southern gap (Figure 4.10).

With the closer of the roof opening in the morning, there observed a quick increase of indoor air temperature (about 1 to 2 °C) due to equalization of the temperature of the indoor air and element of concrete surface around it

During daytime, the increase of air temperature after the initial jump was very moderate (around 3 °C for the whole day). This indicates the effectiveness of the high mass of in storing the nocturnal cold energy.

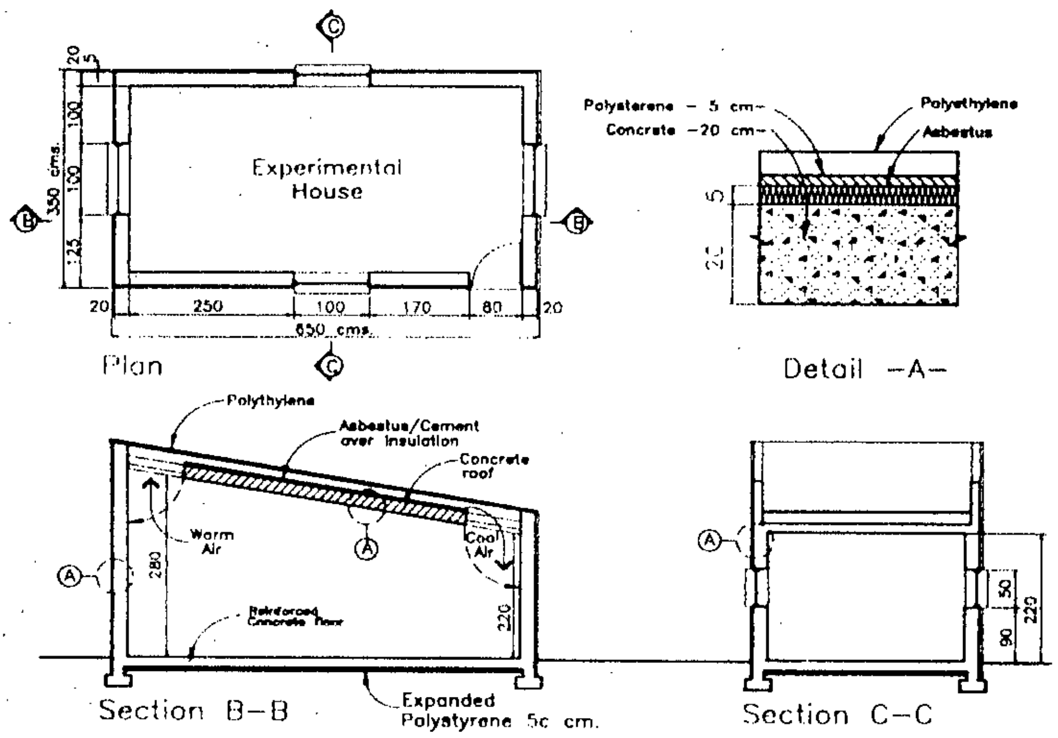

Figure 4.10 The test room, cooled by an asbestos-cement radiator in Eilat, Israel. (Source Givoni and Hoffman 1970)

It can also be seen that around 3A.M. the outdoor temperature became lower than the indoor. Actually when the windows were open with roof openings, there was a sharp rise of indoor temperature.

It should be noted that the performance of this system deteriorated with time. Part of the deterioration was due to dust accumulation on the polyethylene, which reduces its transparency to long wave radiation and in part to a higher humidity level. This study faced the practical problem in the use of polyethylene windscreen. The screen has to be cleaned frequently due to dust accumulation which is very troublesome even for a single room and in case of full sized building, cleaning is not a practical proposal. Even with the cleaning the thermal performance of the system as well as the polyethylene material gradually deteriorated.

c) **Unglazed Solar Collectors used as Nocturnal Radiators**

The idea of utilizing unglazed solar collectors as nocturnal radiators for summer cooling and as solar collectors for winter heating was suggested by Mc Cormic and Landro (1980). The system comprise of a radiator/collector and a rock pile thermal storage with ducting and fan for the control of airflow. At night, the cooled air can be directed to the rock store or can be drawn directly into the rooms.

A Roof Pond cooled by Unglazed Solar Collectors: Etzion and Erell, at institute for Desert Research of Ben Gurion University, Israel have used copper tube attached to a copper plate as unglazed water heating solar collectors (Etzion and Erell 1991).

The test chamber measuring 2 x 2 m (external), 1.6 x 1.6 m (internal) x 2 m high (internal) structure with concrete floors and walls made of hollow concrete blocks. The structure was insulated with 5 cm thick polystyrene and plastered. The concrete roof was 10 thick with a water pond over it, serving as thermal storage with floating insulation panels over the water.

During the night hours in summer, the pond water was circulated through the unglazed collectors, cooling the pond and the concrete roof beneath it. In winter the process was reversed, and the water circulation took place during daytime, thus heating the water. Heat flow between the pond and the room below was by conduction through the roof. Figure 4.11 (Etzion and Erell 1991) illustrates diurnal patterns of outdoor air, indoor air and ceiling water temperature of three days in August 1988. The outdoor minimum and maximum temperatures were about 19 °C and 33.5 °C respectively. The daily average indoor temperature was about 23.5 °C, which was about 2.7 °C below the outdoors average. The average maximum temperature was about 24.2 °C.

The temperature of the water circulating through the unglazed collectors was higher than the outdoor between about 22.00 and 6.00 hrs. Thus convective cooling accompanied the radiant heat loss most of the night.

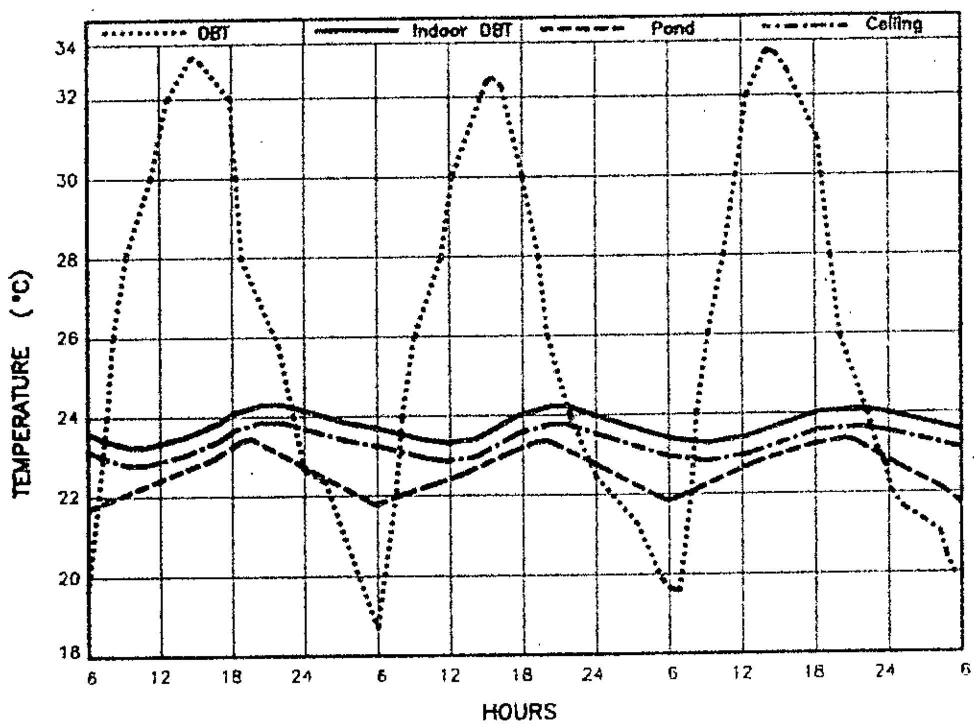

Figure 4.11 Indoor air, ceiling and pond temperatures in a test cell cooled by unglazed solar collectors acting nocturnal radiators. (Source: Etzion and Erell 1991)

The measured average total radiant and convective cooling rate of water was about 55 W/m^2, which is lower than expected in a desert area from a radiator at a temperature higher than the ambient one. Cause was due to resistance to the heat flow from tubes to the cooler radiating areas in between, but the large collector to floor area ratio apparently has provided a total cooling rate sufficient to achieve remarkable temperature reduction.

f) The Roof Radiation Trap

Based on the findings of Eilat buildings showing impracticality of using polyethylene windscreen and to incorporate passive solar heating in the system for winter, Givoni (Givoni 1977) has proposed a system called 'Roof radiation Trap' which is a passive solar heating and nocturnal radiant cooling system for the buildings with concrete roofs. The radiation trap has an inclined fixed insulation layer on the south above the concrete roof. Painted corrugated metal sheets (nocturnal radiators) are placed above the roof insulation acting as a channel for outdoor air flow under radiator during night time. The southern gap between concrete roof and insulation is glazed and a hinged insulation panel is attached to it to serve in winter as a solar radiation trap (Figure 4.12)

In summer when radiation trap is used for cooling, prevention of incoming solar radiation through southern gap is done by closing the gap with the help of hinged insulation panels. At night the painted metal layer is cooled by outgoing radiation and the air under the corrugated sheet is driven into the building. In winter, the hinged panels in the southern gap is kept open during daytime allowing solar radiation to penetrate through the glazing and is absorbed in the black painted concrete roof. The panel is closed during night and the concrete roof serves as a radiant heating panel for the space below.

The performance of the radiator under stagnation conditions and when air flows under it was tested by Givoni at the Institute for Desert Research of Ben Gurion, University in Sede Boqer, Israel. A small lightweight model (internal dimension 50 x 100 cm) was constructed with 50 mm polystyrene plate sandwiched between plywood sheets. The roof was inclined at the height of 50 cm and was covered by light gray painted corrugated aluminum as nocturnal radiator with 3 mm air gap between the roof and radiator. Outdoor air is sucked during night by a small exhaust fan installed inside the model.

Diurnal temperature pattern of DBT and radiator under stagnation condition shows even before the sunset around 4 PM the radiator's temperature fall below the ambient temperature as the long wave radiation began to exceed the convective gain. The temperature difference increased until, at about 9 PM, a stable temperature drop of about 7 to 8 °C was established. After midnight temperature drop fluctuated, probably because of change in the wind speed and /or cloudiness.

Before the start of the fan operation (4 PM till 8 PM) the drop of temperature was similar to stagnation experiment. However with the start of the forced air flow, the rate of cooling by the radiator decreased and the temperature drop after the initiation of the flow was about 3 to 4 °C until 1 PM when probably passing clouds markedly reduce temperature drop.

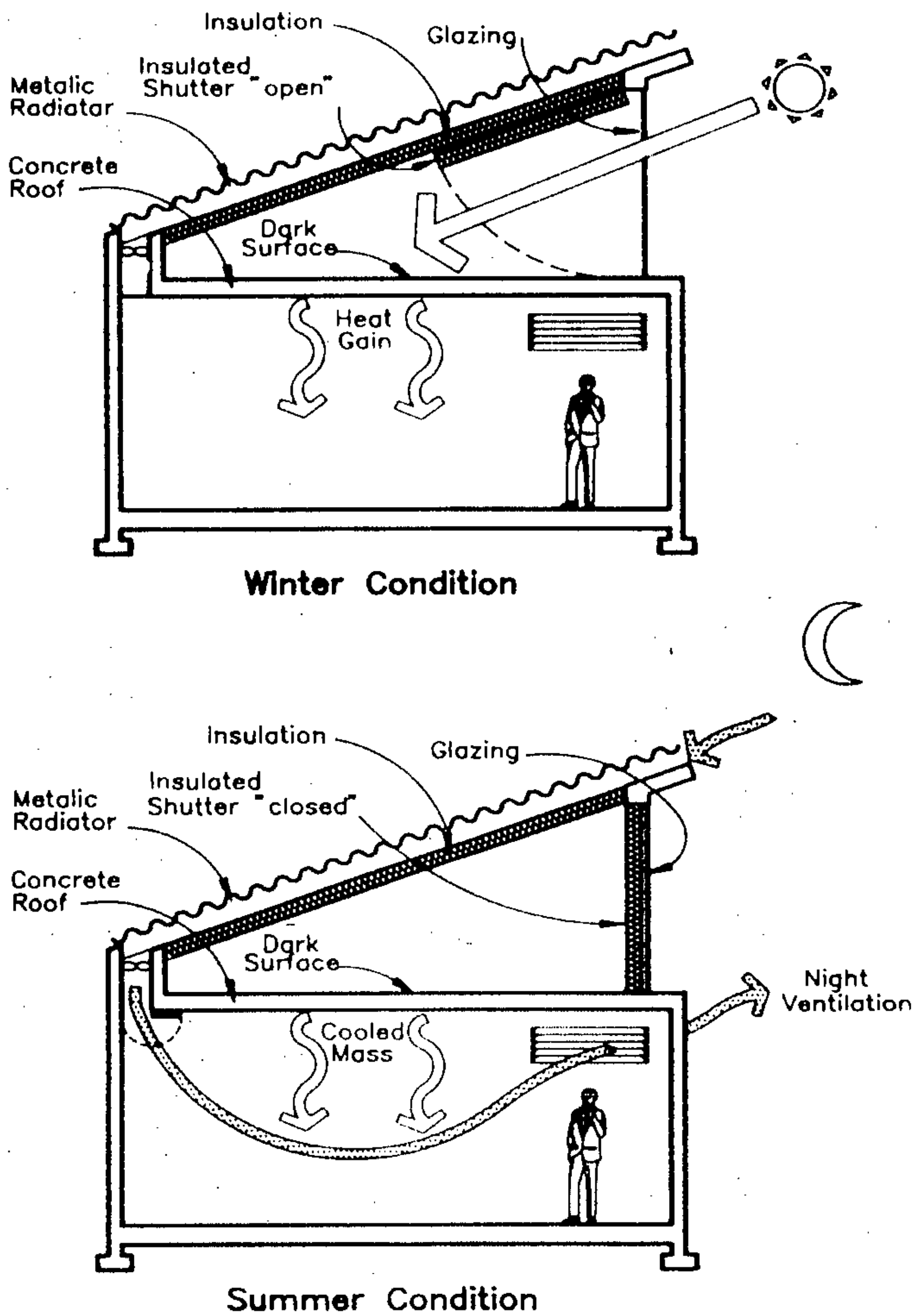

Figure 4.12 The working principle of Roof Radiation Trap. (Source Givini 1994)

The staked air was cooled by the radiator and as the fan was rather small producing low flow rate, at the exit the air reached a temperature very close to the average temperature of the radiator. Thus, the air flowing under the radiator was cooled about half of the stagnation temperature depression.

g) Metallic and Asbestos-Cement Roof in Developing Countries

Corrugated metal or asbestos-cement roofs are widely used in many developing countries. The low mass roof cools down rather quickly during night acting as nocturnal radiator, located directly above the living space. The internal night condition of these kinds of buildings are often more comfortable than buildings with high-mass roof. But during daytime the indoor climatic condition of these buildings are often uncomfortably hot as the uninsulated lightweight roofs are heated up to much higher temperature than the concrete roofs.

Installing centrally hinged parallel insulating panels under the roof can largely reduce daytime heating without interfering too much with cooling effect of such roofs at night. During the daytime when the insulating panels are in horizontal position (closed), they act like a continuous insulation layer under the roof resisting heat flow to interior space. During night as the panels are turned into vertical position enabling radiant and convective heat flow from the interior space to the ceiling, which is cooled by the long wave radiation to the sky (Figure 4.13).

As the internal insulating panels are nor exposed to rain and wind, it can be simpler in construction and lighter and less expensive than external insulating panels. Position change of these interior-insulating panels can be done manually by means of rope (which is not always convenient). A major potential hazard with interior insulation that is made of expanded plastic materials is fire. However designing with noncombustible operable interior insulation can reduce the risk.

During the nights in hot-humid regions, indoor water vapor may condense on the interior surface of the metallic roof. This is most likely when the radiator is metallic, but may also happen when thin asbestos-cement sheets are used.

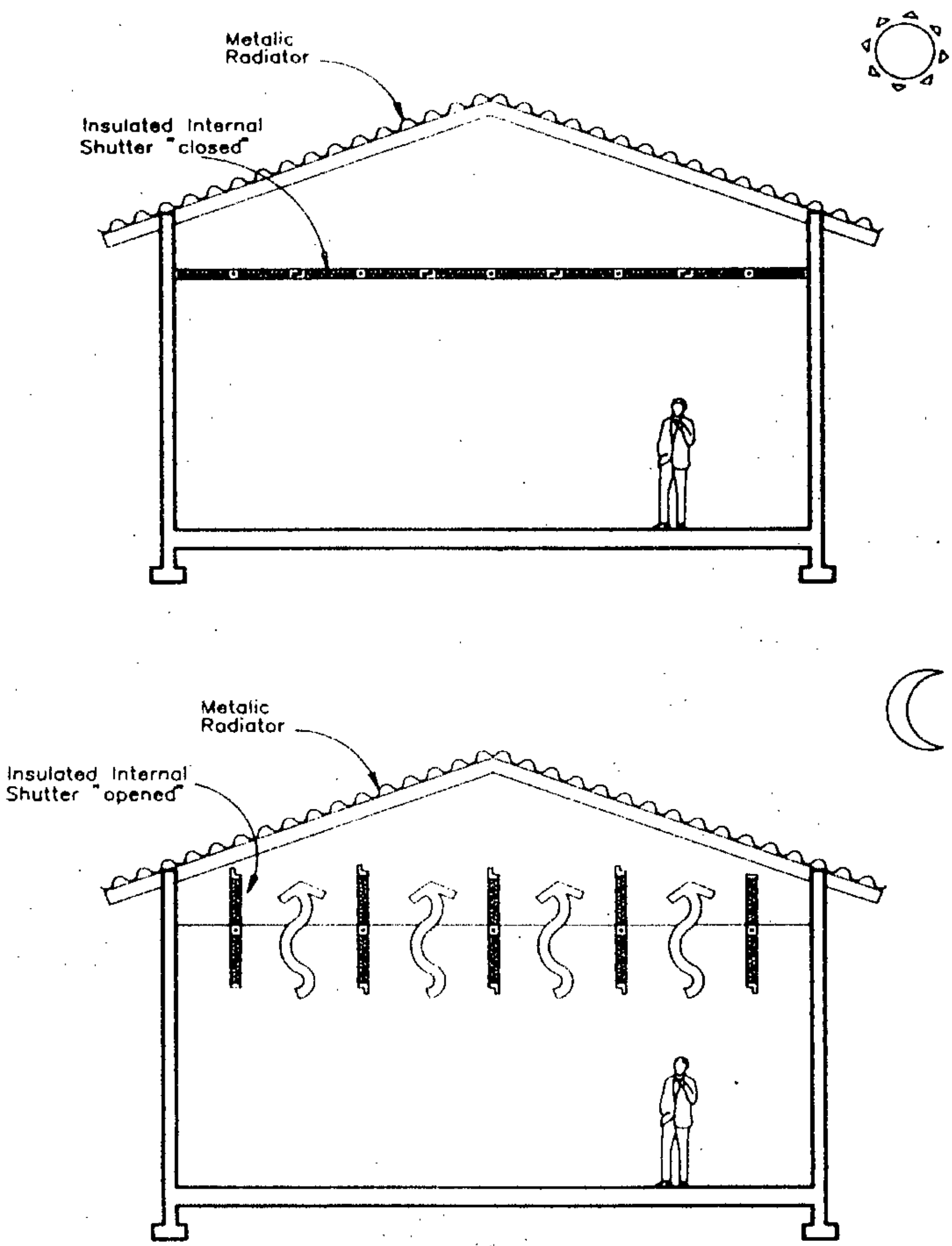

Figure 4.13 A scheme for utilizing metallic roof in developing countries as a nocturnal radiators with daytime insulation from the roof. (Source Givoni 1994)

Design detail of collection and drainage of the condensate can actually lower the interior humidity level and enhance the comfort of the occupants.

4.5 CONCLUSION

The applicability of radiant cooling as a major method of heat dissipation from a building depends on the type of the building, especially on the structure of the roof. The thermal performance of radiant cooling and expediency of its application depends greatly on the climate. As radiant cooling takes place only at night, for buildings that are occupied during the evening hours in regions lacking night wind with high ambient temperatures (above comfort level), the method's benefit is almost instantaneous. However, in order to get benefit from nocturnal radiant cooling during the following daytime hours the cold generated by the radiator has to be stored in a thermal-storage mass. By ventilating the building with the cooled air, the cooling process also cooling down the structural mass of the building. The cooled mass serves, during the following day, as a passive sink for heat, which is, generated inside the building or that go through the building's envelop (Givoni 1994).

From the information presented in this chapter, it is evident that the best prospect of radiant cooling happens in arid regions with clear skies and low wind speed at night during summer. In this situation the potential for radiant cooling maximized for all the different systems, where it is possible to reduce the indoor temperature 3 to 4 °C below the ambient air temperature. However in humid regions with predominantly clear skies and still air during night, radiant cooling can be regarded as practical option where ambient night air can be cooled by about 2 to 3 °C by nocturnal radiation. Situation can be further improved by dehumidification of air introduced into the building.

On the contrary, in regions with predominantly cloudy sky and/or high wind speed at night the net radiant loss is too small (usually 1 °C below the ambient air temperature) and hard to justify the cooling system based on radiant heat loss. This situation is different when radiant heat loss is supplemented by convection (in case of high mass-roof), coupled with operable insulation, serves the radiator. With high mass radiators the temperature of the radiating surface is above the ambient temperature most of the night.

Radiant heat loss is thus increased by the higher temperature of the radiator, in addition to the convective cooling of the thermal storage that is an integral component of the system.

When examining building types, it should be noted that due to the low intensity of radiant heat loss, a building requires a large area of radiator for significant cooling. As the roof is the most reasonable location for nocturnal radiator, radiant cooling is applicable almost entirely to single story building or top floor of multistory building.

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CHAPTER FIVE

THERMAL PERFORMANCE OF OPERABLE ROOF INSULATION: SIMULATION STUDY

5.1 INTRODUCTION

The thermal performance of Roof Insulation and its impact on indoor environment can precisely be identified by simulation study. Because in reality, due to the simultaneous influence of many different conditions it is difficult to isolate the exclusive effect of one single aspect or the changes of it. Thermal simulation allows study of the effect of changes in one aspect keeping other factors constant. The observations of simulated behavior that occur due to changing parameters allow the identification of elements, the reduction or introduction of which in the design contribute to indoor comfort. Furthermore, this study will narrow down the options of insulation parameter among a wide variety of combinations for most effective result (which would be very time consuming and troublesome to work with all options of insulation in real situation). Another significant achievement of simulation study is that, it is possible to analyze the thermal performance of operable roof insulation for any period of the year simply by assigning simulation parameters (like temperature, radiation, wind speed & direction relative humidity cloud cover). A dynamic computer simulation program named A-Tas (version 8.30) has been used for this simulation study. The interpretation of simulated temperatures is related to measured conditions of empirical comfort criteria (chapter Three).

5.2 OVERVIEW OF THE SIMULATION PROGRAM

A-Tas is a program[1], which simulates the thermal performance of buildings. The main applications of the program are in assessment of environmental performance, natural ventilation analysis, prediction of energy consumption, plant sizing, analysis of energy conservation options and energy targeting.

A-Tas is linked to the 3D modeller, 3D-Tas. Together these two programs go by the name **Tas Lite**. The fundamental approach adopted by A-Tas is dynamic simulation. This technique traces the thermal state of the building through a series of hourly snapshots, providing the user with a detailed picture of the way the building will perform, not only under extreme design conditions, but throughout a typical year. This approach allows the

[1] The details of the simulation program is based on the reference manual provided with the software

influences of the numerous thermal processes occurring in the building, their timing, location and interaction, to be properly accounted for. These processes are illustrated schematically in Figure 5.1, which shows the movement of heat in various forms as it is conveyed into, out of and around the building by a variety of heat transfer mechanisms.

Conduction in the fabric of the building is treated dynamically using a normal co-ordinate method[2]. This efficient computational procedure calculates conductive heat flows at the surfaces of walls and other building elements as functions of the temperature histories at those surfaces. Constructions of up to 12 layers may be treated, where each layer may be composed of an opaque material, a transparent material or a gas. Convection at building surfaces is treated using a combination of empirical and theoretical relationships relating convective heat flow to temperature difference, surface orientation, and, in the case of external convection, wind speed. Long-wave radiation exchange is modelled using the Stefan-Boltzmann law, using surface emissivities from the materials database. Long-wave radiation from the sky and the ground is treated using empirical relationships. Solar radiation absorbed, reflected and transmitted by each element of the building is computed from solar data on the weather file. The calculation entails resolving the radiation into direct and diffuse components and calculating the incident fluxes using knowledge of sun position and empirical models of sky radiation. Absorption, reflection and transmission are then computed from the thermophysical properties of the building elements. External shading and the tracking of sun patches around room surfaces may be included at the user's option

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[2] 'Time-varying conduction heat transfer and heat storage in the building fabric is modelled in Tas using the normal co-ordinate method[a] with a time-step of 1 hour. The method is closely related to methods based on Response Factors and Conduction Transfer Functions[c] but offers substantial run-time and storage savings relative to these methods. The following summary is taken from Ref. 'a':

The basis of the method is a description of the thermal state of the wall in terms of a set of normal co-ordinate variables. These variables, which define a decomposition of the temperature and flux distributions in the wall in terms of eigenfunctions, are updated at each time increment, and are used, in combination with recent input data, to calculate all output quantities. The method thus possesses elements in common with the two most widely used of existing methods for the analysis of wall heat flows, combining an economical state-representation resembling that employed by finite difference methods with fast and accurate techniques borrowed from response factor theory.
The method assumes linear, uni-dimensional heat flow, and relies on analytical techniques developed by Pipes[b] and Stephenson and Mitalas[c]. Data is accepted in the form of regularly sampled surface temperatures, and values are generated for the temperature or heat flux at any desired point within the wall. Minor modifications, reported elsewhere[d], allow for boundary conditions involving the specification of heat flux in place of temperature at either surface. Other extensions of the method, described in reference d, include provision for alternative interpolation procedures, the calculation of time integrals of output variables, and methods for dealing with non-linear surface characteristics. The method can also be adapted to model varying time-steps." (after A-Tas reference manual)

a. M. Gough. A new method for the calculation of heat transfer in walls and roofs. CIB International Symposium on System Simulation in Buildings, Liege, Belgium, Dec 6-9 1982.
b. L.A. Pipes. Matrix analysis of heat transfer problems. *Franklin Institute Journal*, Vol. 263(3), March 1957.
c. D.G. Stephenson, G.P. Mitalas. Calculation of heat conduction transfer functions for multi-layer slabs. *ASHRAE Trans.* 1971, Vol. 77, II,
d. M.C.B. Gough. Modelling heat flow in buildings: an eigenfunction approach. PhD dissertation, University of Cambridge. 1982.

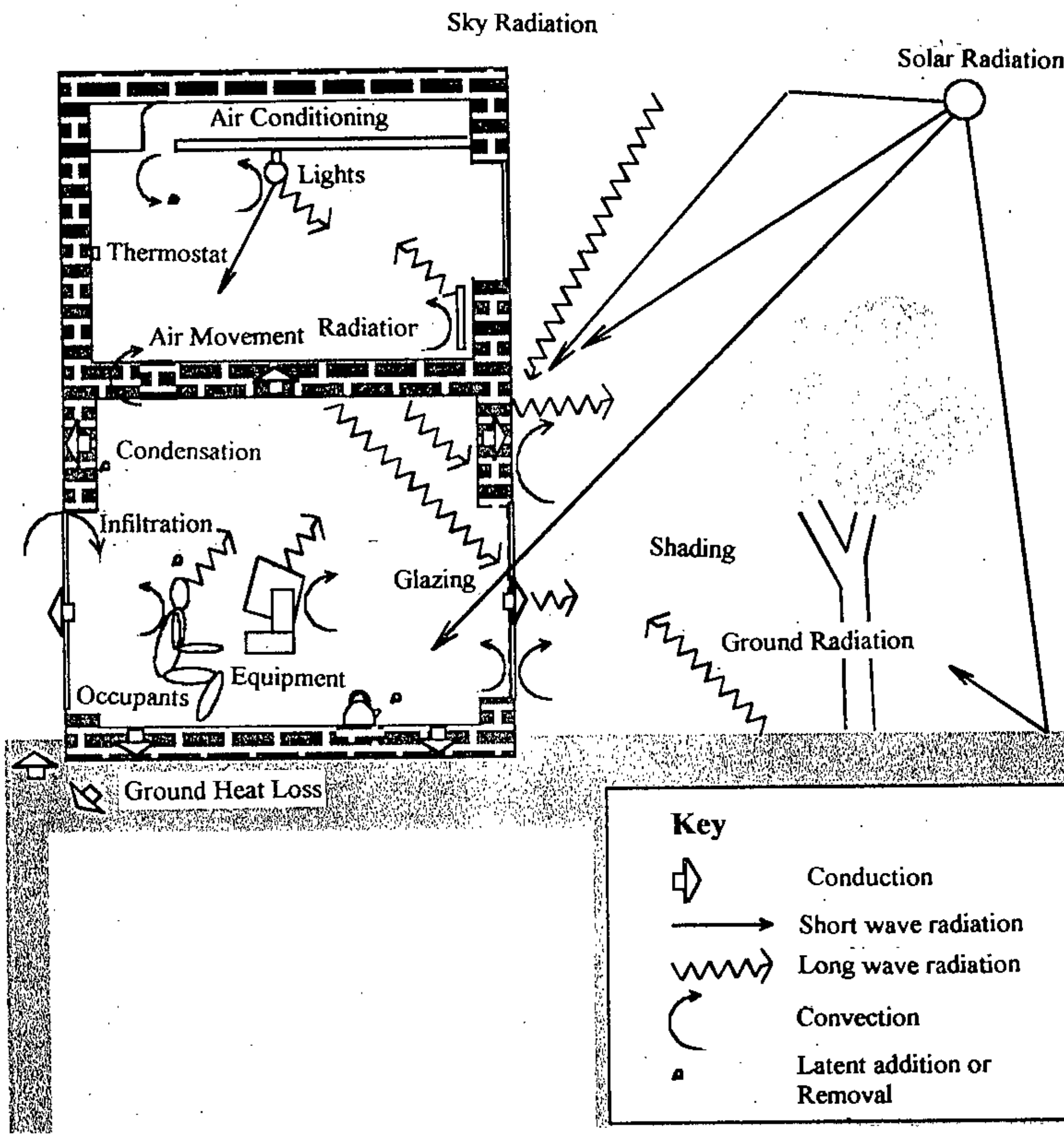


Figure 5.1 Schematic Representation of Heat Transfer mechanism in a Building (after A-Tas)

5.3 THERMAL SIMULATION STUDY

5.3.1 Test Room Modelling

The criteria for site and building selection was based on the following factors:

- The site should be urban in nature and capable of representing the general urban fabric of Dhaka city:
- Test room should be a single storied building or should be located on the top floor of a multistoried building.

According to the above criteria the Test room on the top floor of a 4-storied building was selected at was selected at Monipuri Para (near national assembly complex)

The Test room dimension is 4.19 m X 3.68 m. located at the north-east corner of the site in which north and east wells are exterior walls, while south and west is blocked by other functions. Actually the test room is a part of a complete residence with other bedrooms, living room, dining, kitchen, toilets etc. but they are deducted to simplify the simulation operation. Only the functions (identified as zone) that have direct bearing to the test room are considered for test room modelling in simulation program (Figure 5.2).

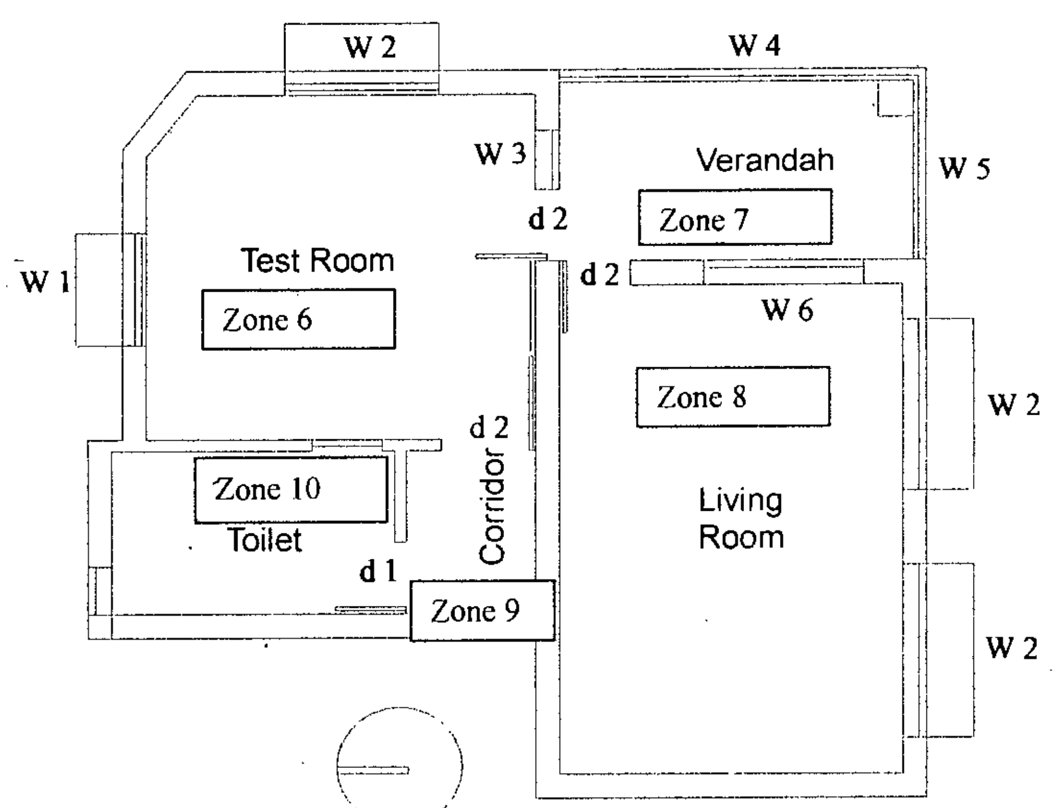


Figure 5.2 Test room modeling by A-Tas where unnecessary zones (which has no bearing to test room) have been removed.

5.3.2 Preparation of Databases

The Tas databases contain data, which is regularly required for building model preparation and evaluation. There are databases of i) Climate ii) Internal Conditions iii) Materials iv) Constructions. Climate and Internal database have to be prepared on the basis of site parameters and Test room condition while Materials and Construction database are in built with the program and can be arranged in different combinations.

i) Climate

The Climate Database stores files containing hourly weather data. The weather files supplied with Tas cover different regions of the world and each represents a typical year's weather for the region in question. The name of each weather file is prefixed with a country identifier (for example 'Ban_' for Bangladesh). Facilities are provided to allow creating own weather files and can be added to the Climate Database.

A weather file consists of a group of parameters relating to the weather site and hourly values of seven weather variables. The weather file 'Ban_Dhaka.wfl[2]' has been prepared for the research purpose, where three hourly weather data has been collected from Climate Division, Bangladesh Meteorological Department Agargaon, Dhaka. Due to the simulation program requirements all three hourly data has been converted to hourly data by interpolation method.

The site parameters of weather file are as follows:

Parameters	Details
Latitude (degrees North)	23 Deg. 46 mts. N
Longitude (degrees E)	90 Deg. 23 mts. E
Time Zone (hours ahead of GMT)	GMT + 06.00
Ground Temperature (deg. C)	25.8 degrees Celsius

Hourly weather variables for Dhaka has been collected for the year 2000 on the basis of following categories:

[2] Hourly climatic data for the year 2000 were sent to the product support manager of Environmental Design Solution Limited and EDSL programmers developed this weather file for the specific research.

Hourly weather variables	Details
1. Global Radiation ("global")	Total solar radiation intensity on a horizontal plane.
2. Diffuse Radiation ("diffuse")	Diffuse sky radiation intensity on a horizontal plane.
3. Cloud Cover ("cloud")	A number varying from 0 for a clear sky to 1 for overcast conditions. This quantity is used to estimate long-wave sky radiation during simulation.
4. Dry-bulb Temperature ("t")	The dry-bulb temperature as measured in a Stephenson screen.
5. Relative Humidity ("rh")	The relative humidity as measured in a Stephenson screen.
6. Wind Speed ("wspeed")	The wind speed measured at a height of 10 meters above the ground
7. Wind Direction ("wdirec")	The direction from which the wind blows (degrees east of north).

The combination of site parameters and hourly weather variables forms the **weather** file, with which the simulation program (A-Tas) is able to analyse any climatic characteristics of the selected site.

ii) Internal Conditions/ Test Room Conditions

Internal conditions include room gains from lights, equipment and occupants as well as infiltration rates and plant operation specifications are grouped together in profiles, which are applied to the various zones of the building. Internal Conditions profiles may be stored in a database for later retrieval. Gains are modelled by resolving them into radiant and convective portions. The convective portion is injected into the zone air, whilst the radiant gains are distributed amongst the zone's surfaces. Infiltration, ventilation and air movement between the various zones of the building causes a transfer of heat between the appropriate air masses which is represented by terms involving the mass flow, the temperature difference and the heat capacity of air. Tas offers the capability to calculate natural ventilation air flows arising from wind and stack pressures. Solar radiation entering a zone through transparent building components falls on internal surfaces, where it may be absorbed, reflected or transmitted depending on the surfaces' properties. Distribution of reflected and transmitted solar radiation continues until all the radiation has been accounted for. Tas solves the sensible heat balance for a zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is solved simultaneously to generate air temperatures, surface temperatures and room loads. This procedure is repeated for each hour of the simulation. A latent balance is also performed for each zone, which takes account of latent gains, moisture transfer by air movement and the operation of humidification and dehumidification plant. (for specific internal condition of the test room see section (h) & (i) of Appendix 3.1)

The following are some of the factors, which influence the thermal behaviour of a building, and whose influences A-Tas allows the user to investigate:

- Thermal insulation
- Thermal capacity ("thermal mass")
- Glazing properties
- Built form and orientation
- Climate
- Shading from nearby buildings and self-shading
- Infiltration
- Natural ventilation
- Mechanical ventilation
- Solar gain
- Gains from lights, occupants and equipment (both sensible and latent)
- Control setpoints & bands, optimum start, frost protection
- Available plant capacities for heating and cooling
- Plant schedules
- Plant radiant/convective characteristics
- Performance of boilers and heat pumps

A-Tas provides output in graphical and tabular form showing the effects of these factors on:

- Air temperature
- Mean radiant temperature
- Resultant temperature
- Surface temperatures
- Humidity
- Condensation risk

- Sensible and latent loads
- Energy consumption
- Required plant size

iii) Materials

The Materials Database stores data on the thermophysical properties of building materials. Data on a wide selection of materials is supplied with the Tas program. Materials are used as constituents for construction types in the Constructions Database. Each material is identified by a Material code, which consists of two parts: the material category and the item number. The material category is characters identifying a class of materials (for example insulating materials). The item number is an integer, which identifies an individual material within the category. (See section (d) of Appendix 3.23 for the materials specifically used for the test room and roof insulation)

iv) Constructions

The Constructions Database stores construction types for walls, floors, etc. built up from layers composed of materials from the materials database. No constructions are supplied with the Tas program.
Each construction type is identified by a construction code, which consists of two parts: the construction category and the item number. The construction category is a name identifying a class of construction types. The item number is an integer that identifies an individual construction type within the category. (also see section (d) of appendix 3.23 for the construction details of the test room and roof insulation)

5.4 DISCUSSION OF RESULTS: THERMAL PERFORMANCE OF ROOF INSULATION

Significant findings of environmental condition of the Test room (which is located at the top floor of a 4 storied building in Dhaka) are discussed in this section to evaluate thermal performance of roof insulation (see also Appendix 3). The section is divided into following (1) Simulation Output: Uninsulated Roof (2) Simulation Output: Roof with Insulation. The aim of this investigation is to study the thermal performance of roof insulation Therefore uninsulated roof has been considered as a base case to which insulation on roof at different height can be compared. In evaluation process certain environmental criteria like Indoor Temperature, Mean Radiant Temperature and Ceiling Temperature in the test room, which are directly influenced by roof insulation, have been considered Insulation top temperature has also been taken into account as roof insulation is influenced by this factor.

5.4.1 Simulation Output: Uninsulated Roof

In order to evaluate the thermal performance of roof insulation a base case situation was established by studying the uninsulated roof during the month of June. June is selected because it represents the Monsoon or hot-wet period and characterized by high humidity, high temperature, and high cloud cover and high radiation. The clearness index is low. Moreover in the context of Dhaka Monsoon is the most prolonged season among others (for more detail see chapter Two and appendix 5).

a) Indoor Air Temperature

Indoor temperature of a room depends on certain external factors, where roof insulation can play an important role. The significant findings of temperature data recorded from simulation program for the test room without roof insulation case are described below:

The average temperature recorded during data generation by the computer simulation was 32.74 °C, which is just above the comfort level with still air situation. The max temperature was logged as 36.1 °C while the minimum was 29.9 °C making a difference of 6.2 °K. The highest outdoor temperature was recorded on the same day as 33.6 °C and testifies it's bearing on indoor temperature. Diurnal difference of maximum and minimum temperature ranges between 2.6 °K to 6.2 °K, while the time lag between them varies by 8 to 9 hours. (Figure 5.3.1, 5.3.2 and 5.3.3)

It is evident from the logged temperature profile for the selected days that they follow almost identical trends specially the time of attainment of day maximum and minimum temperature. The indoor temperature was over the comfort range for most of the period during data collection

b) Mean Radiant Temperature (MRT)

MRT is an average temperature of the surrounding surfaces. It includes the effect of incident solar radiation and has as great an impact as air temperature.

The average MRT generated in the test room is 36.27 °C, which is way above comfort range even in this situation air flow at the rate of.45m/s is unable to create comfortable environment. The maximum temperature was registered over 40 °C and the minimum near 33 °C. The difference is 7 °K. Temperature difference between daily max and min ranges between 4.6 °K to 7 °K and the time lag was always 10 hours between them. (Figure 5.4.1, 5.4.2 and 5.4.3)

From the observation of the simulated data it is evident that MRT always reaches to its peak after outdoor temperature, thus creates a time lag of 1 to 2 hours. As the minimum temperature is above the comfort range in still air condition, a warm condition prevails in the test room.

c) Ceiling Temperature

As ceiling is closely associated with the roof and also due to its physical positioning, any temperature fluctuation on roof directly and immediately affects ceiling temperature. A warm ceiling increases indoor temperature of the room below by convection and radiation process, therefore it is a significant factor to be considered.

According to the logged data, the maximum ceiling temperature was recorded as 44.9 °C, while the minimum was 32.2 °C, thus creating a difference of 12.7 °K. Diurnal difference of maximum and minimum temperature ranges between 7.4 °K to 12.7 °K and the time lag ranges between 7 to 10 hours. (Figure 5.5.1, 5.5.2 and 5.5.3)

The temperature profile indicates that it increases the indoor temperature of the test room thus creating an uncomfortable situation.

d) Surface Temperature of Insulation (Top)

It is most directly related with the thermal profile of the roof insulation. According to the simulation data, the average insulation top temperature was recorded as 38.74 °C, while the maximum and minimum are 54.5 °C and 29.4 °C during the period of data collection. The diurnal variation between maximum and minimum temperature ranges by 19 °K to 29 °K and the time lag of daily maximum and minimum temperature occurrence varies between 7 to 9 hours. (Figure 5.5.1, 5.5.2 and 5.5.3)

It is evident from the recorded data that diurnal temperature difference is significant and a quick rise of temperature is observed during noon and prevailed for couple of hours. This phenomenon obviously increase the indoor temperature of the test room

5.4.2 Simulation Output: Roof with Insulation

With operable insulation system data were collected at two different height (also to study whether there is any impact of height), first at 500 mm above the roof which is the close to the minimum height of parapet generally used in Dhaka and then at 200 mm above the roof which comes from the width of the Styrofoam panel, used as insulation material for the roof (see also chapter six).

i) At 500 mm above the Roof

Simulation study was performed in the test room, with insulation for the month of April, which falls in pre-monsoon or hot-dry period. Temperature pattern is most pronounced during this season. In the case of Dhaka it is evident from solar radiation data and atmospheric clearness index (see chapter two) that during this month high radiation influx is the major factor contributing to the difference in temperature observed. Thus it is the most critical among all other months of the year and chosen for investigation. Significant findings of environmental data collected from simulation study for the test room with roof insulation at 500 mm above the roof are described below

a) Indoor Air Temperature

Indoor temperature of a room bank on certain external issues, and roof insulation is one of the significant factors. The major findings of temperature data are as follows:

The average temperature recorded during data collection was 27.24°C, which is well within the comfort level with still air situation. The max temperature was logged as 33 °C while the minimum was 22.2 °C making a difference of 10.8 °K. The highest outdoor temperature was recorded on the same day when indoor temperature reached to its peak as 33 °C and testifies it's influence on indoor temperature as other days of data recording there observed lower temperature profile. Diurnal difference of maximum and minimum temperature ranges between 7.7 °K to 8.4 °K, (much higher diurnal difference than uninsulated roof) while the time lag between them varies by 5 to 8 hours. (Figure 5.6.1, 5.6.2 and 5.6.3)

A gradual decrease of diurnal average temperature is observed, as the temperatures are 29.48, 27.65 and 24.6 °C respectively. It is evident from above facts that roof insulation has profound impact on indoor temperature. It prevents the increase of temperature by reducing incoming radiation from the roof, hence increase thermal comfort.

b) Mean Radiant Temperature (MRT)

MRT is an important factor to be considered in thermal performance evaluation. It includes the effect of incident solar radiation and has as great an influence as air temperature.

The average MRT recoded in the test room is 30.50 °C, which is within comfort range and much lower than uninsulated roof. The maximum temperature was registered as33.7 °C and the minimum as27.3 °C. The difference is 6.4 °K. Temperature difference between daily max and min ranges between 3.5 °K to 6.4 °K (Figure 5.7.1, 5.7.2 and 5.7.3).

During all the measured days MRT as a major descriptor of thermal comfort, except couple of hours was always within comfort temperáture range in still air condition. Above circumstances testify that roof insulation has influence on MRT as it obstructs the major passage of incoming heat through roof and help reducing radiant temperature to ensure thermal comfort.

c) Ceiling Temperature

Due to close proximity any temperature fluctuation on roof directly and immediately affects ceiling temperature, so it is a significant factor to be considered.

According to the logged data, the maximum ceiling temperature was recorded as 32.9 °C, while in the case of uninsulated roof it was 44.9 °C. the min .temperature recorded as 28.9 °C, thus creating a difference of 4 °K with insulated situtation. The time lag ranges between 7 to 13 hours Diurnal difference of maximum and minimum temperature ranges between 1.9 °K to 3.1 °K , whereas for uninsulated roof it was 7.4 °K to 12.7 °K. So temperature fluctuation is greatly reduced which ensures better thermal environment and at the same time performance of roof insulation. (Figure 5.8.1, 5.8.2 and 5.8.3)

The daily average ceiling temperature for data recording days are 31.49, 31.46 and 30.20 °C respectively, which is within comfort range. It should be noted that the average temperature is decreasing from starting day-to ending day of data collection with the introduction of roof insulation. It is obvious from the all above facts that roof insulation has profound bearing on ceiling temperature.

d) Surface Temperature of Insulation (Top)

It is most directly related with the thermal profile of the roof insulation. According to the simulation data, the average surface temperature of insulation top was recorded as 35.09 °C, while the maximum and minimum are 60.1 °C and 20.3 °C during the period of data collection. The diurnal variation between maximum and minimum temperature ranges by 30.9 °K to 37.9 °K and the time lag of daily maximum and minimum temperature occurrence varies between 4 to 6 hours. (Figure 5.8.1, 5.8.2 and 5.8.3)

It is evident from the recorded data that diurnal temperature difference is significant and a quick rise of temperature is observed during noon and prevailed for some hours, which should have major influence on the thermal environment in the test room hence the thermal comfort. But with the introduction of roof insulation, we experience a much better situation in the test room

ii) At 200 mm above the Roof

Simulation study was performed in the test room, with insulation for the month of May, which is representative of hot-dry season and characterized by high temperature and radiation. Cloud cover is over five octa and longer sunshine hour is observed (see chapter two and appendix 5 for more detail). This month is also climatologically very important.

a) Indoor Air Temperature

Significant findings of weather data received from simulation study for the test room with roof insulation at 200 mm above the roof are described below

The average temperature recorded during data collection was 31.86 °C, which is within the comfort level with still air situation. The max temperature logged as 36.4 °C while the minimum was 25.4 °C making a difference of 11 °K. The magnitude of the highest outdoor temperature was same as the indoor on the same day. Diurnal difference of maximum and minimum temperature ranges between 6.8 °K to 9.4 °K, while the time lag between them is 8 hours in all instances. . (Figure 5.9.1, 5.9.2 and 5.9.3)

A gradual increase of average temperature is observed in above circumstances, as the average temperatures are 30.73 °C, 32.05 °C and 32.82 °C respectively. It is evident from above facts that performance of roof insulation is reversed as compared to situation of insulation at 5oo mm height from the roof .

b) Mean Radiant Temperature (MRT)

The average MRT recoded in the test room is 34.97 °C, which is above comfort range. The maximum temperature was registered as 37.7 °C and the minimum as 30.9 °C. The difference is 6.8 °K. Temperature difference between daily max and min ranges between 4.3 °K to 5.1 °K and the time lag varies between 2 to 9 hours between them. . (Figure 5.10.1, 5.10.2 and 5.10.3).

From the observation of the recorded data it is evident that MRT always reaches to its peak at the same time when outdoor temperature reaches to its peak, thus creates no time lag. During measured days MRT as is major descriptor of thermal comfort, except couple of morning hours in starting data collection day was always above comfort temperature range in still air condition.

c) Ceiling Temperature

As a significant factor to be considered .the major findings are:

According to the logged data, the average temperature was recorded as 35.55 °C and maximum ceiling temperature was recorded as 38.4 °C, while the minimum was 32.3 °C, thus creating a difference of 6.1 °K. Diurnal difference of maximum and minimum temperature ranges between 3.6 °K to 4 °K as compared to 7.4 °K to 12.7 °K for uninsulated roof, testifying a much stable condition. The time lag ranges between 9 to 11 hours. (Figure 5.11.1, 5.11.2 and 5.11.3)

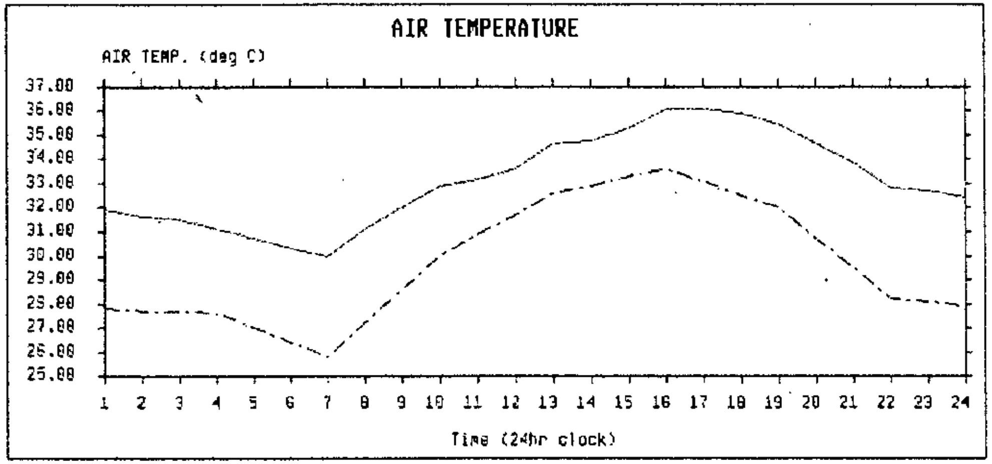
The average ceiling temperature for simulated days are 34.4, 35.67 and 36.57 °C respectively, which is above comfort range of previous mentioned criteria.

d) Surface Temperature of Insulation (Top)

According to the simulation data, the average surface temperature of insulation top was recorded as 43.93 °C, while the maximum and minimum are 73.9 °C and 25.3 °C during the period of data collection. The diurnal variation between maximum and minimum temperature varies over 40°K and the time lag of daily maximum and minimum temperature occurrence varies between 5 to 6 hours. (Figure 5.11.1, 5.11.2 and 5.11.3)

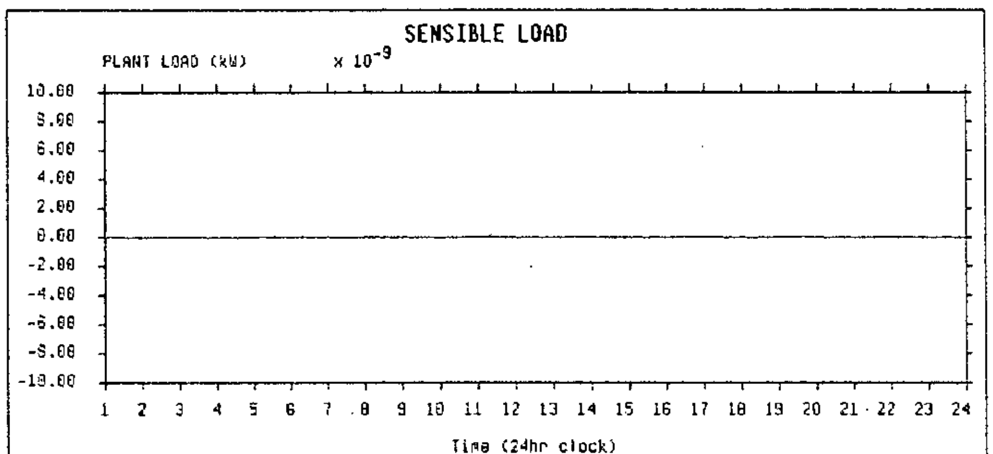
It is evident from the recorded data that diurnal temperature difference is significant and a quick rise of temperature is observed during noon and prevailed for couple of hours, which could elevate indoor thermal condition way above the comfort level, but because of the insulation on the rooftop a much better thermal environment is attained in the test room.

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
23	T2Room	T2Room.bdf.01	84	20:19:01	03:Jul:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	

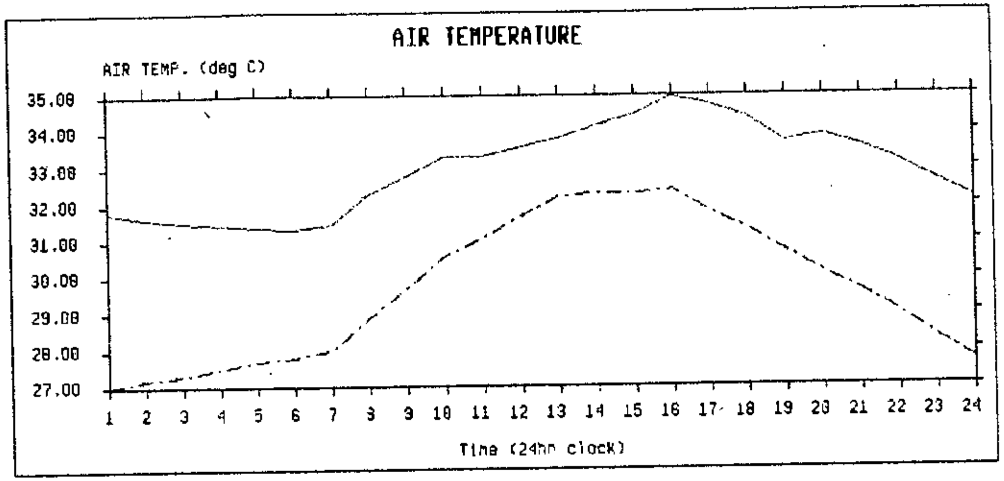
Zone	Cooling (kWh)
6 Test Room	0.00
Outside	



Day 169: Tuesday, Jun 18 (WEEKDAY)
Weather: Ban_Dhaka.wf1

Figure 5.3.1 Temperature Profile in Test Room without Roof Insulation (18 June, 2002)

Page	Building Name	Building Data File	Version	Time	Data	Consultant	Program
24	T2Room	T2Room.bdf.01	84	20:20:53	03:Jul:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	

Zone	Cooling (kWh)
6 Test Room	0.00
Outside	

Day 170: Wednesday, Jun 19 (WEEKDAY)
Weather: Ban_Dhaka.wfl

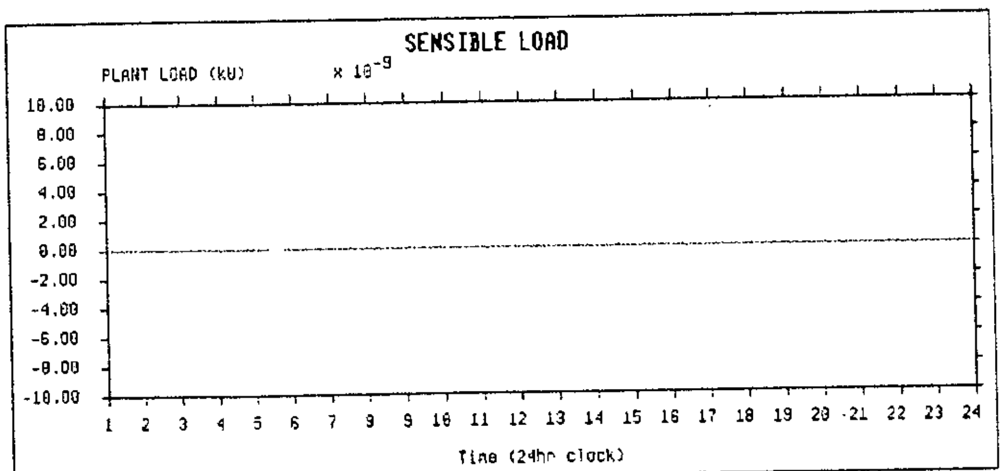
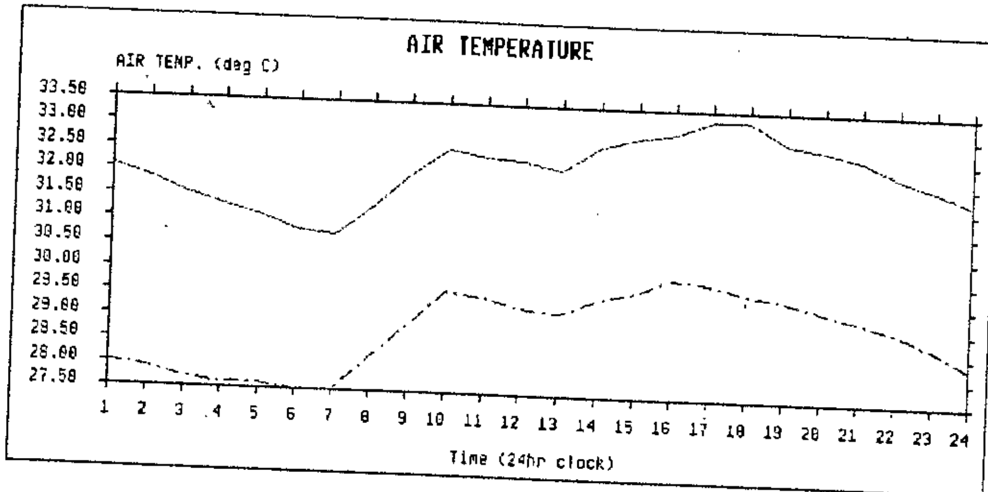
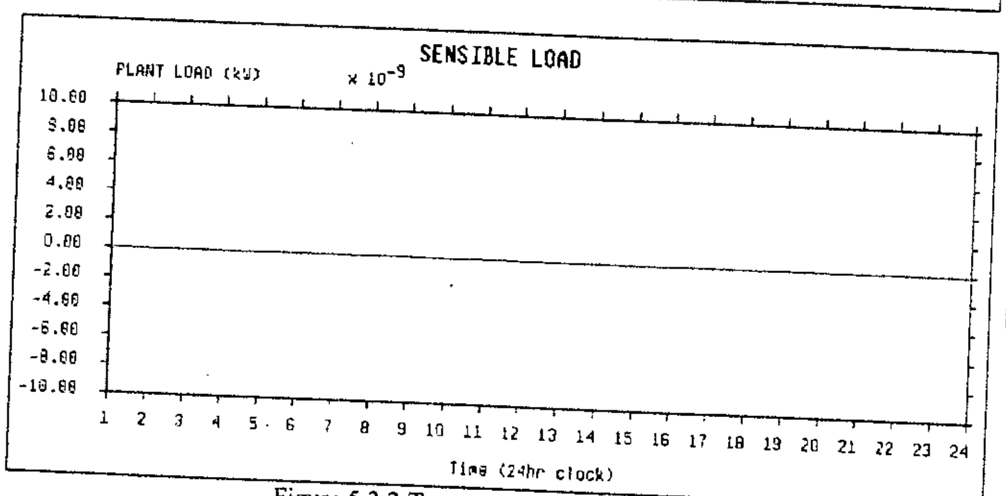


Figure 5.3.2 Temperature Profile in Test Room without Roof Insulation (19 June, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
26	T2Room	T2Room.bdf.01	84	20:21:41	03:Jul:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	



Zone	Cooling (kWh)
6 Test Room	0.00
Outside	

Day 171: Thursday, Jun 20 (WEEKDAY)
Weather: Ban_Dhaka.wf1

Figure 5.3.3 Temperature Profile in Test Room without Roof Insulation (20 June, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
31	T2Room	T2Room.bdf.01	84	20:24:13	03:Jul:02		A-Tas 8.31

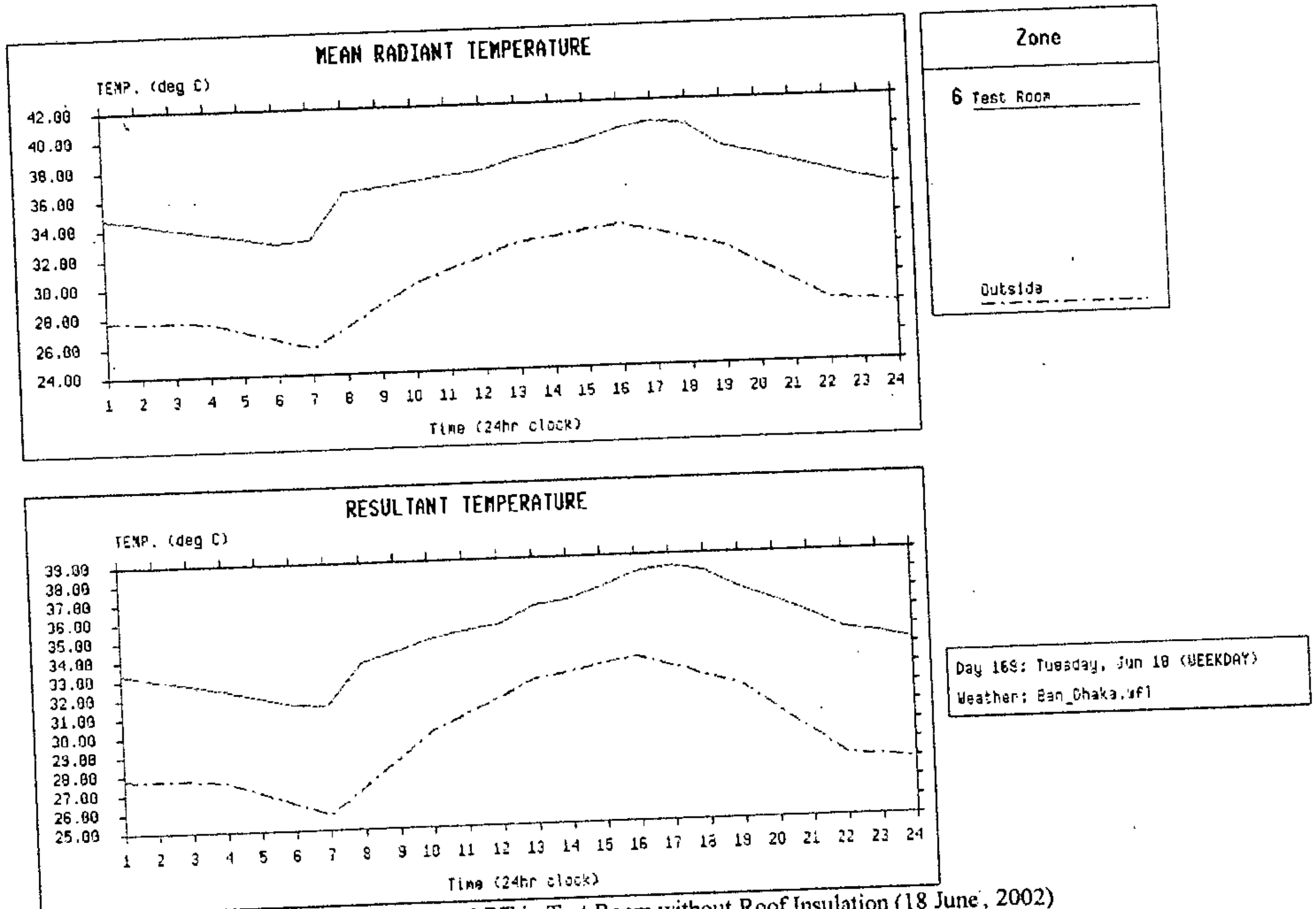


Figure 5.4.1 MRT and RT in Test Room without Roof Insulation (18 June, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
33	T2Room	T2Room.bdf.01	84	20:24:47	03:Jul:02		A-Tas 8.31

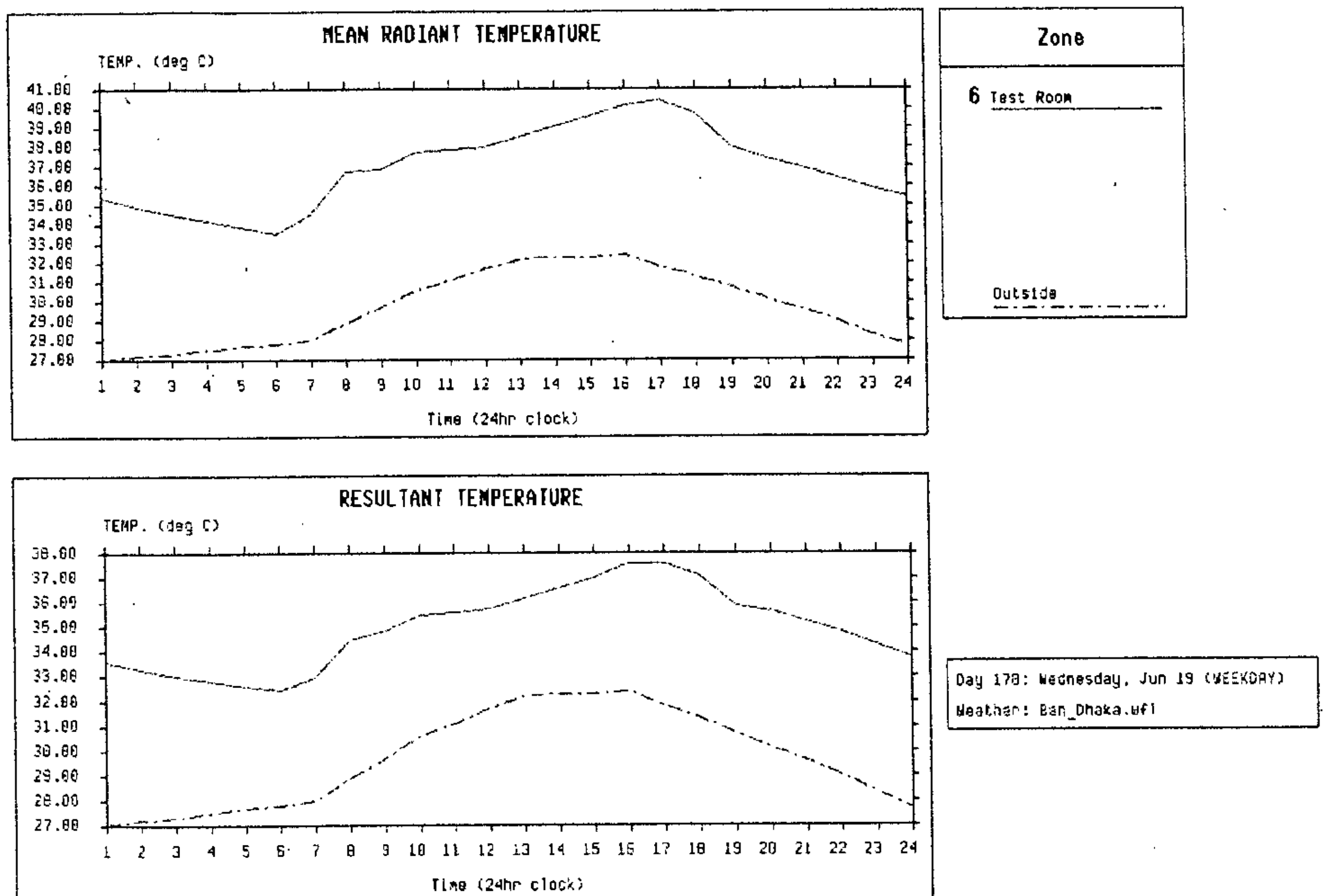


Figure 5.4.2 MRT and RT in Test Room without Roof Insulation (19 June, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
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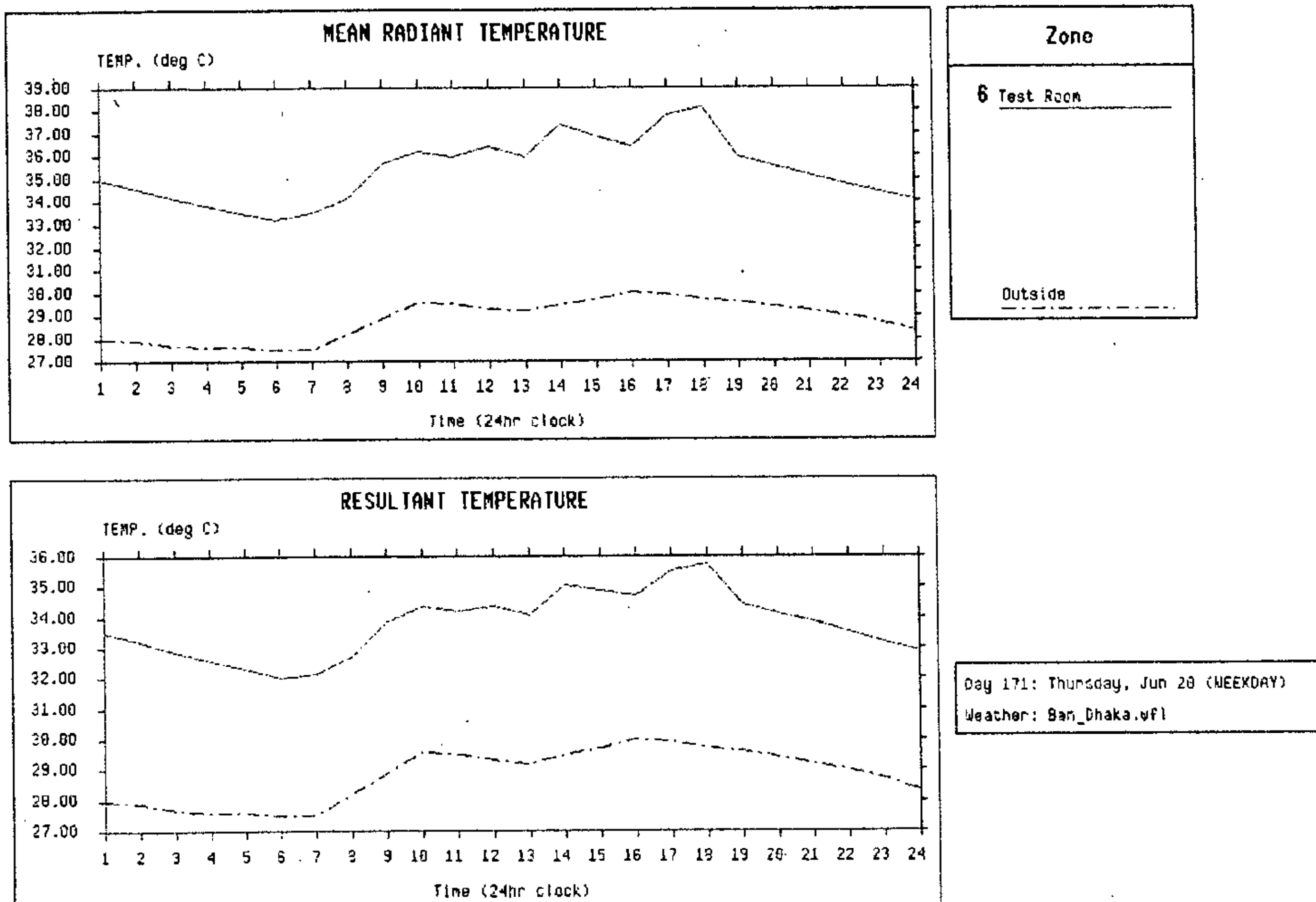
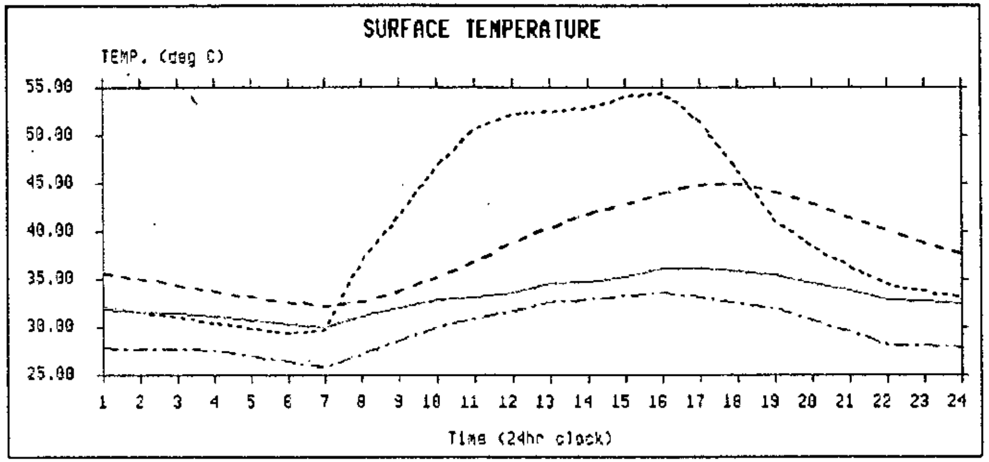


Figure 5.4.3 MRT and RT in Test Room without Roof Insulation (20 June, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
40	T2Room	T2Room.bdf.01	84	20:30:53	03:Jul:02		A-Tas 8.31



	Line Type
Internal Air	————
Internal Surface	- - - - -
External Surface	·········
External Air	—·—·—

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7
Ceiling

Building Feature: Exposed

Orientation: Ceiling

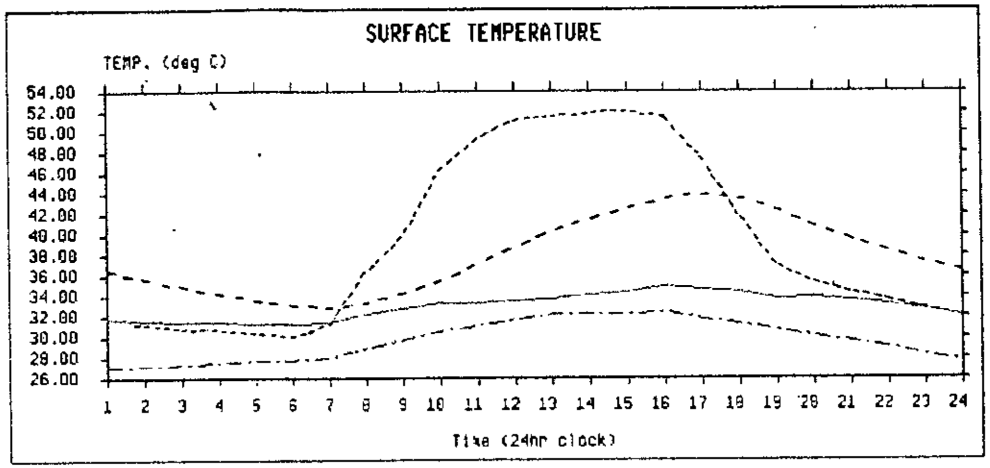
Area (m2): 16.38

Day 169: Tuesday, Jun 18 (WEEKDAY)
Weather: Ban_Dhaka.wfl

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)	Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	35.6	32.2	13	40.4	52.6
2	35.0	31.6	14	41.8	53.0
3	34.3	31.0	15	42.9	54.0
4	33.7	30.4	16	44.0	54.5
5	33.2	29.9	17	44.8	51.4
6	32.6	29.4	18	44.9	46.3
7	32.2	29.7	19	44.1	41.0
8	32.7	37.0	20	42.8	38.4
9	33.8	41.6	21	41.4	36.3
10	35.2	46.9	22	40.0	34.5
11	37.0	50.7	23	38.7	33.7
12	38.8	52.3	24	37.6	33.1

Figure 5.5.1 Surface Temperature of Roof in Test Room without Roof Insulation (18 June, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
41	T2Room	T2Room.bdf.01	84	20:31:39	03:Jul:02		A-Tas 8.31



	Line Type
Internal Air	――――――
Internal Surface	- - - - -
External Surface	··········
External Air	—·—·—·—

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7

Ceiling

Building Feature: Exposed

Orientation: Ceiling

Area (m2): 16.38

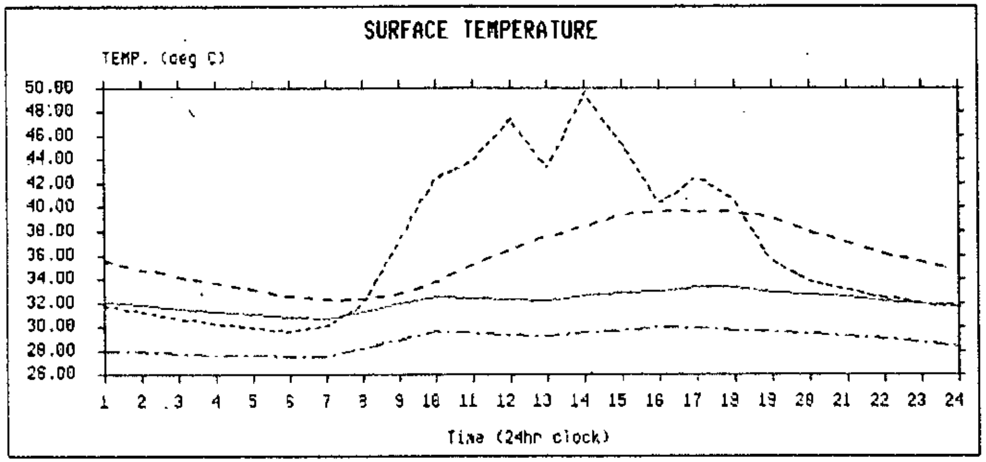
Day 170: Wednesday, Jun 19 (WEEKDAY)

Weather: Ban_Dhaka.wfl

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)	Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	36.6	31.8	13	40.3	51.6
2	35.7	31.3	14	41.5	51.9
3	34.9	30.9	15	42.6	52.0
4	34.2	30.7	16	43.4	51.4
5	33.6	30.4	17	43.9	47.3
6	33.1	30.1	18	43.6	41.7
7	32.9	31.3	19	42.4	37.0
8	33.4	36.4	20	40.9	35.4
9	34.2	39.9	21	39.6	34.4
10	35.5	46.3	22	38.4	33.7
11	37.1	49.4	23	37.3	32.8
12	38.8	51.2	24	36.4	31.9

Figure 5.5.2 Surface Temperature of Roof in Test Room without Roof Insulation (19 June, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
42	T2Room	T2Room.bdf.01	84	20:32:28	03:Jul:02		A-Tas 8.31



	Line Type
Internal Air	———
Internal Surface	- - - - -
External Surface	·········
External Air	-·-·-·

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7

Ceiling

Building Feature: Exposed

Orientation: Ceiling

Area (m2): 16.38

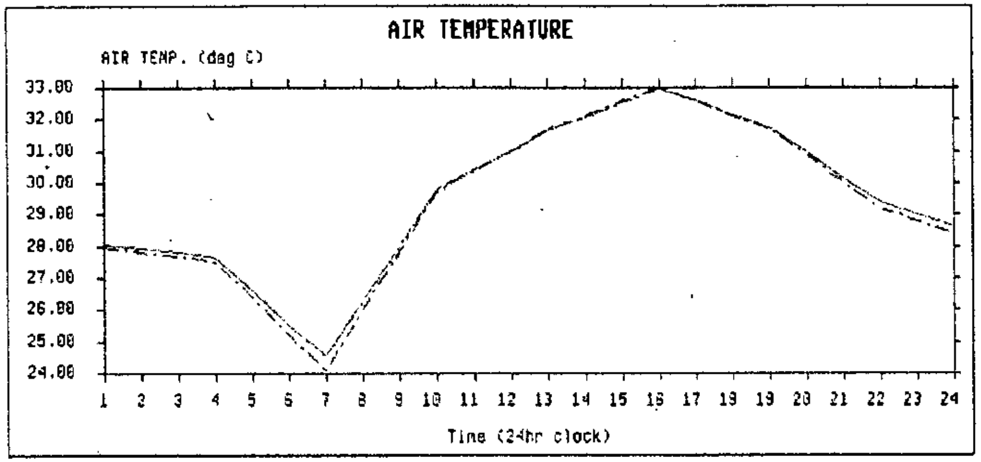
Day 171: Thursday, Jun 20 (WEEKDAY)

Weather: Ban_Dhaka.Wfl

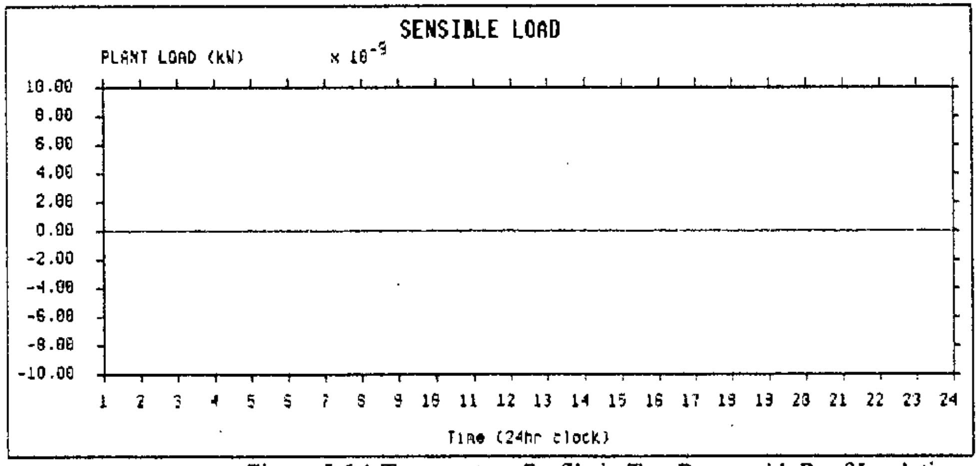
Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)	Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	35.5	31.7	13	37.6	43.4
2	34.8	31.3	14	38.5	49.5
3	34.2	30.7	15	39.5	45.3
4	33.6	30.3	16	39.7	40.4
5	33.1	30.0	17	39.6	42.5
6	32.6	29.6	18	39.7	40.5
7	32.3	30.1	19	39.1	35.4
8	32.3	32.0	20	38.0	33.8
9	32.8	37.4	21	37.0	33.1
10	33.9	42.5	22	36.2	32.5
11	35.2	44.0	23	35.4	32.0
12	36.5	47.3	24	34.7	31.5

Figure 5.5.3 Surface Temperature of Roof in Test Room without Roof Insulation (20 June, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
23	T1Room	T1Room.bdf.01	81	13:06:25	29:Mar:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	

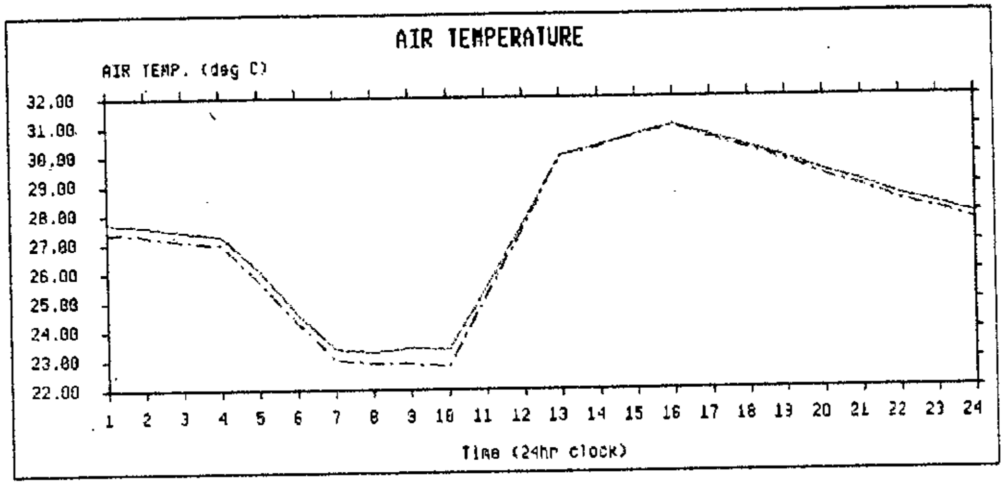


Zone	Cooling (kWh)
6 Test Room	0.00
Outside	

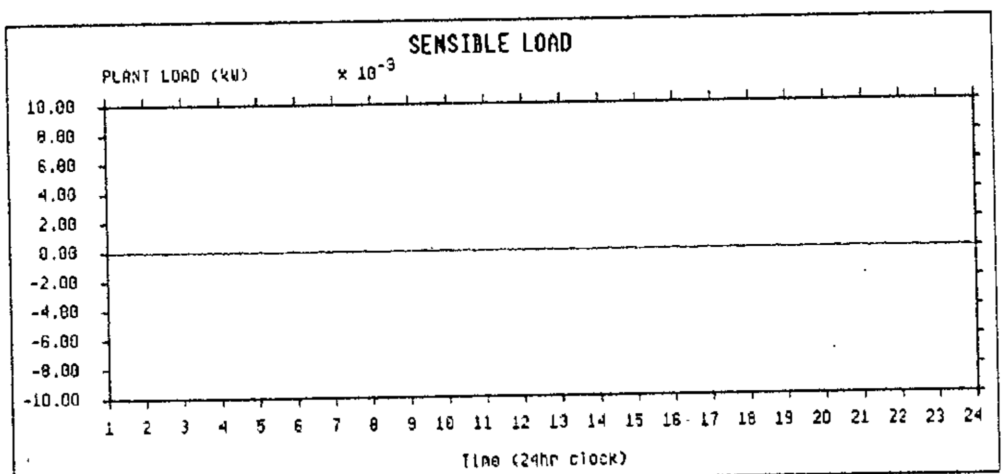
Day 113: Tuesday, Apr 23 (WEEKDAY)
Weather: Ban_Dhaka.wf1

Figure 5.6.1 Temperature Profile in Test Room with Roof Insulation at 500mm (23 April, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
33	T1Room	T1Room.bdf.01	81	13:24:46	29:Mar:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	

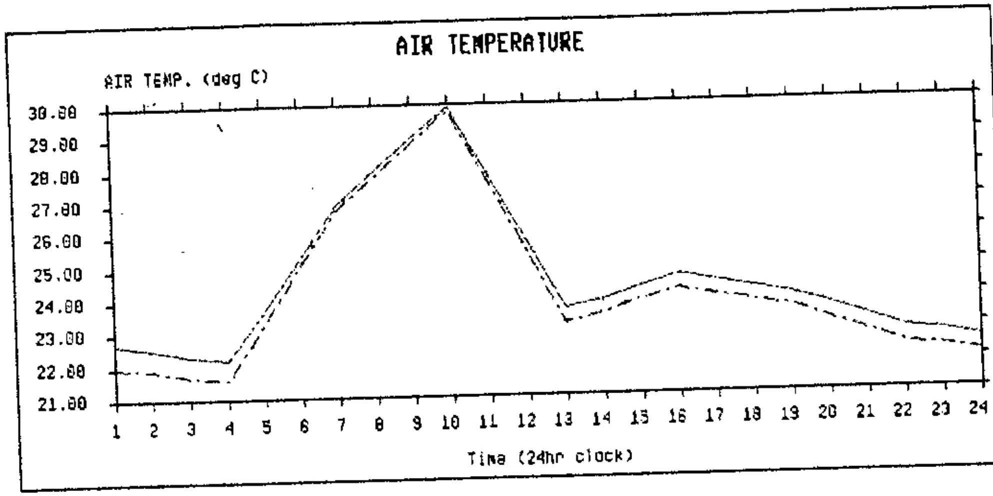


Zone	Cooling (kWh)
6 Test Room	0.00
Outside	

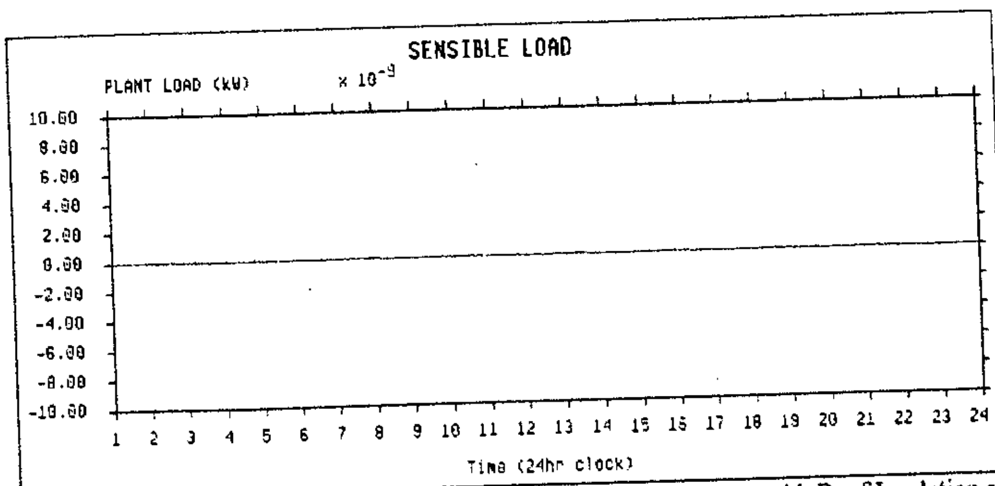
Day 114: Wednesday, Apr 24 (WEEKDAY)
Weather: Ban_Dhaka.wfl

Figure 5.6.2 Temperature Profile in Test Room with Roof Insulation at 500mm (24 April, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
43	T1Room	T1Room.bdf.01	81	13:30:41	29:Mar:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	



Zone	Cooling (kWh)
6 Test Room	0.00
Outside	

Day 115: Thursday, Apr 25 (WEEKDAY)
Weather: Ban_Dhaka.wf1

Figure 5.6.3 Temperature Profile in Test Room with Roof Insulation at 500mm (25 April, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
25	T1Room	T1Room.bdf.01	81	13:08:41	29:Mar:02		A-Tas 8.31

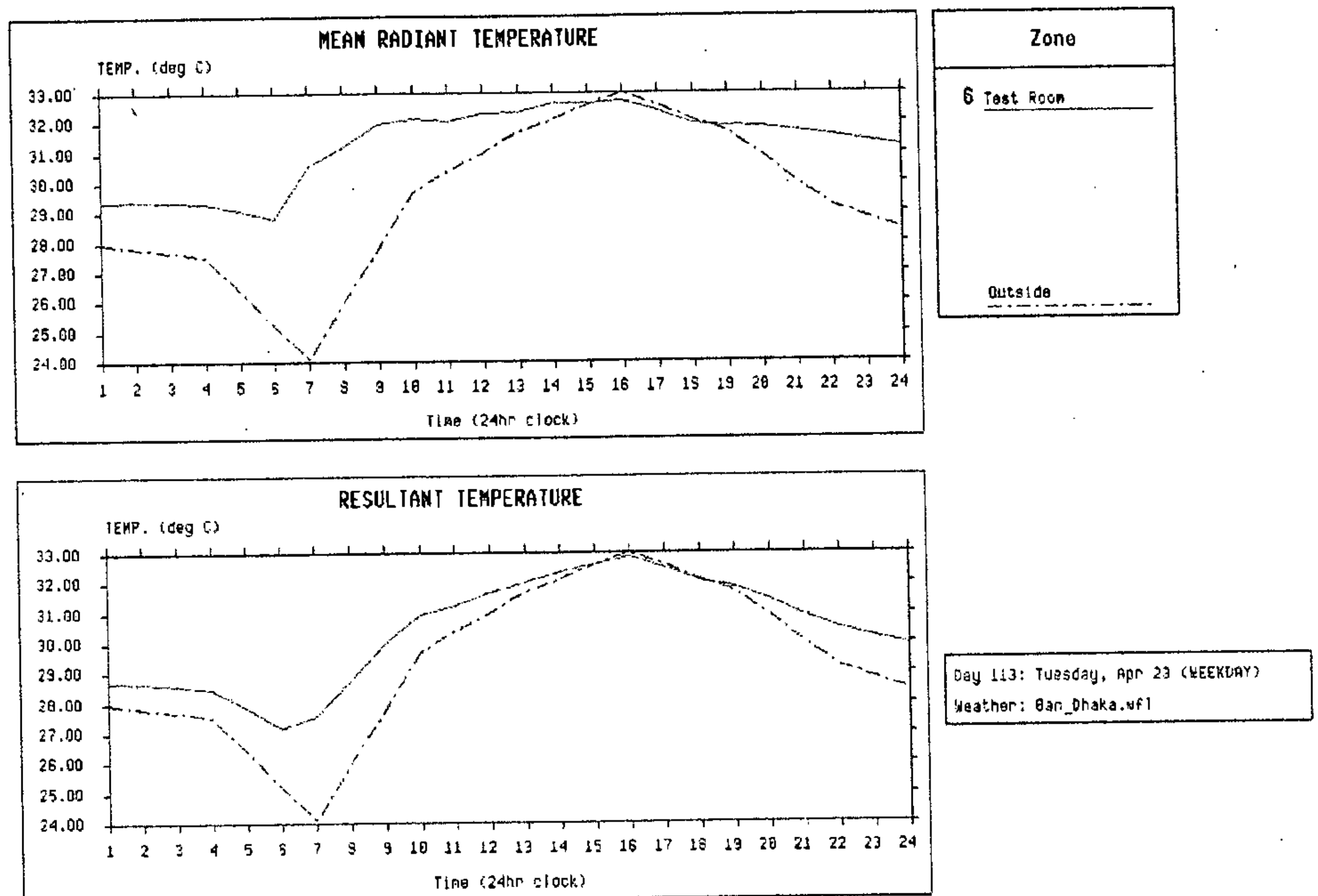


Figure 5.7.1 MRT and RT in Test Room with Roof Insulation at 500mm (23 April, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
35	T1Room	T1Room.bdf.01	81	13:25:54	29:Mar:02		A-Tas 8.31

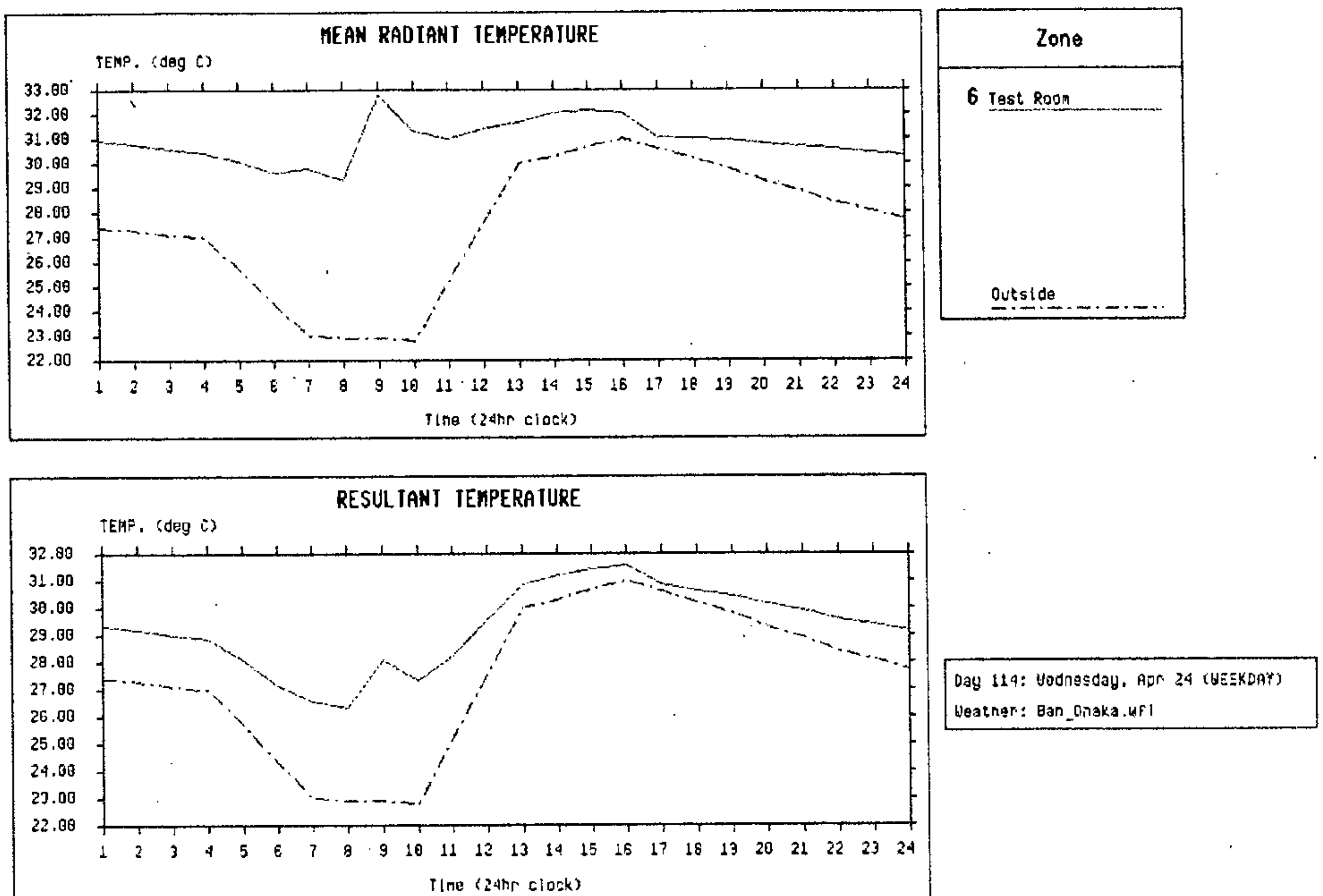


Figure 5.7.2 MRT and RT in Test Room with Roof Insulation at 500mm (24 April, 2002)

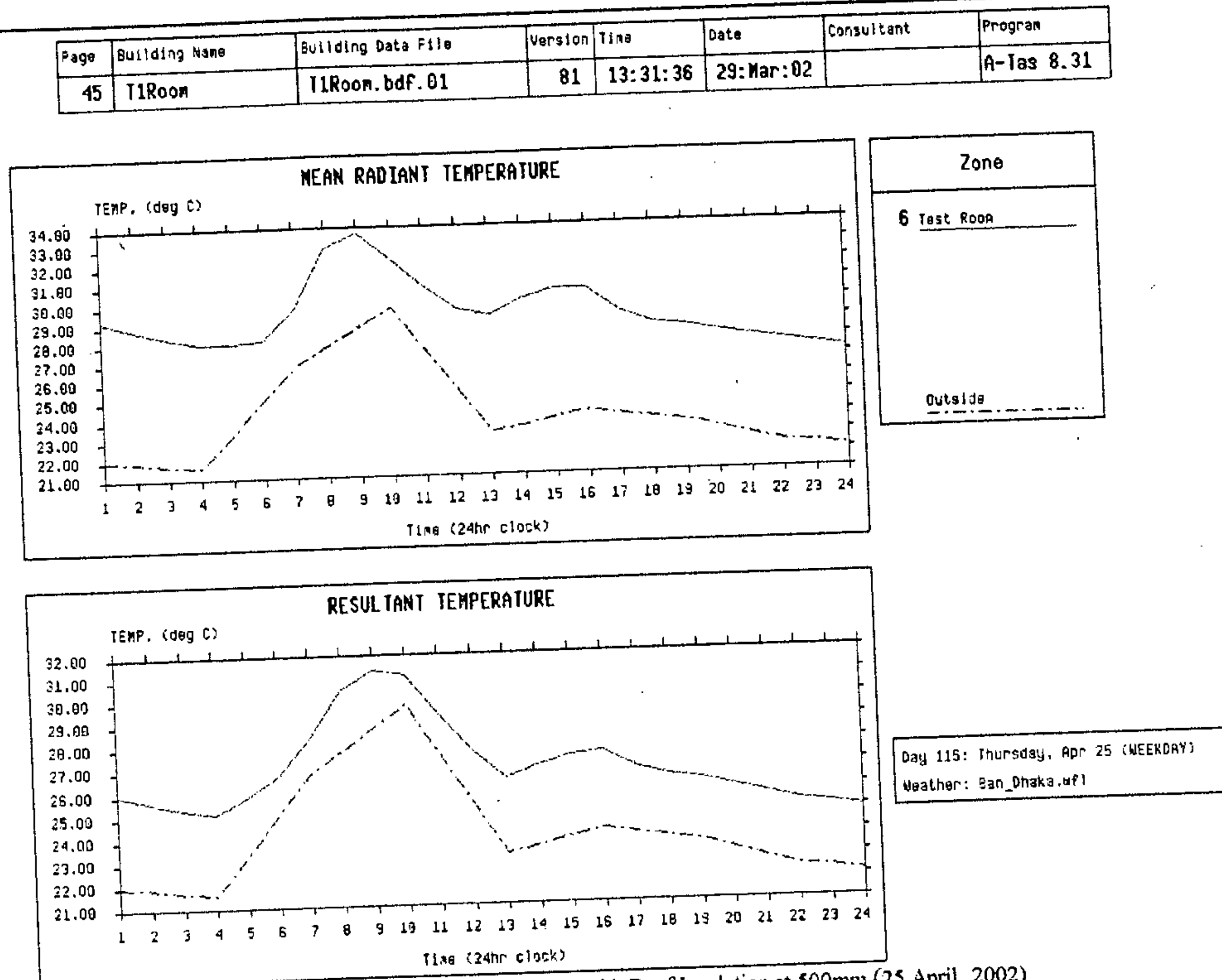
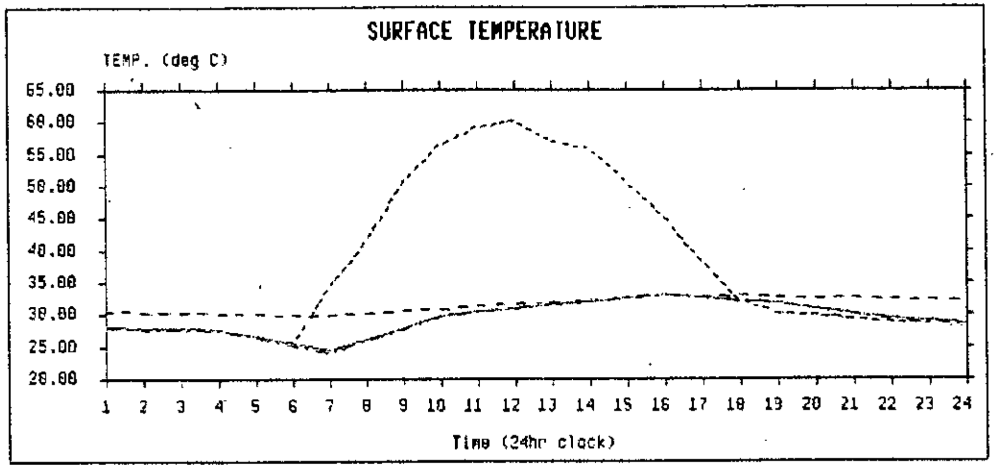


Figure 5.7.3 MRT and RT in Test Room with Roof Insulation at 500mm (25 April, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
28	T1Room	T1Room.bdf.01	81	13:10:22	29:Mar:02		A-Tas 8.31



	Line Type
Internal Air	————
Internal Surface	- - - -
External Surface	··········
External Air	-·-·-·-

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7

Ceiling

Building Feature: Exposed

Orientation: Ceiling

Area (m2): 16.38

Day 113: Tuesday, Apr 23 (WEEKDAY)

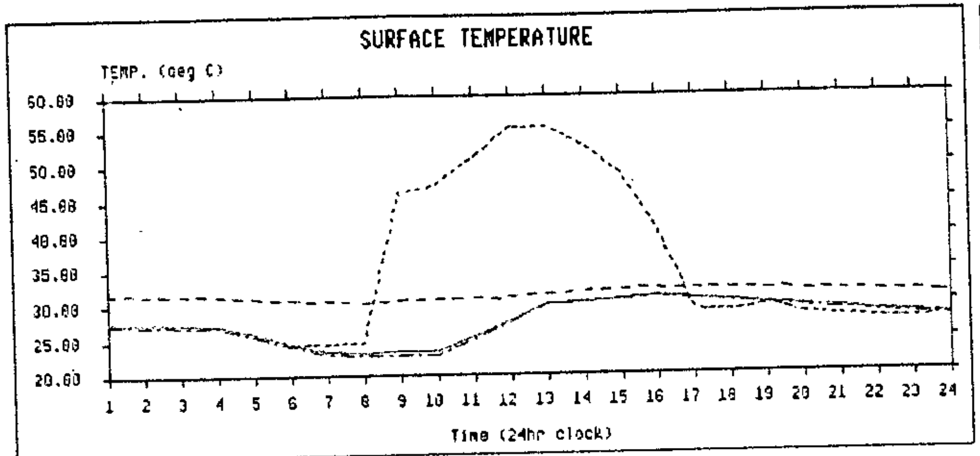
Weather: Ban_Dhaka.wf1

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	30.5	27.5
2	30.4	27.5
3	30.3	27.4
4	30.2	27.7
5	30.0	26.7
6	29.8	25.7
7	29.9	34.4
8	30.2	41.4
9	30.5	50.8
10	30.9	56.4
11	31.3	59.2
12	31.6	60.1

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
13	32.0	57.0
14	32.3	55.8
15	32.6	50.7
16	32.8	44.9
17	32.9	37.8
18	32.9	32.1
19	32.8	30.1
20	32.7	29.8
21	32.5	29.2
22	32.4	28.8
23	32.2	28.4
24	32.1	28.1

Figure 5.8.1 Surface Temperature of Roof in Test Room with Roof Insulation at 500mm (23 April, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
38	T1Room	T1Room.bdf.01	81	13:27:25	29:Mar:02		A-Tas 8.31



	Line Type
Internal Air	————
Internal Surface	- - - -
External Surface	········
External Air	-·-·-·-

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7

Ceiling

Building Feature: Exposed

Orientation: Ceiling

Area (m2): 16.38

Day 114: Wednesday, Apr 24 (WEEKDAY)

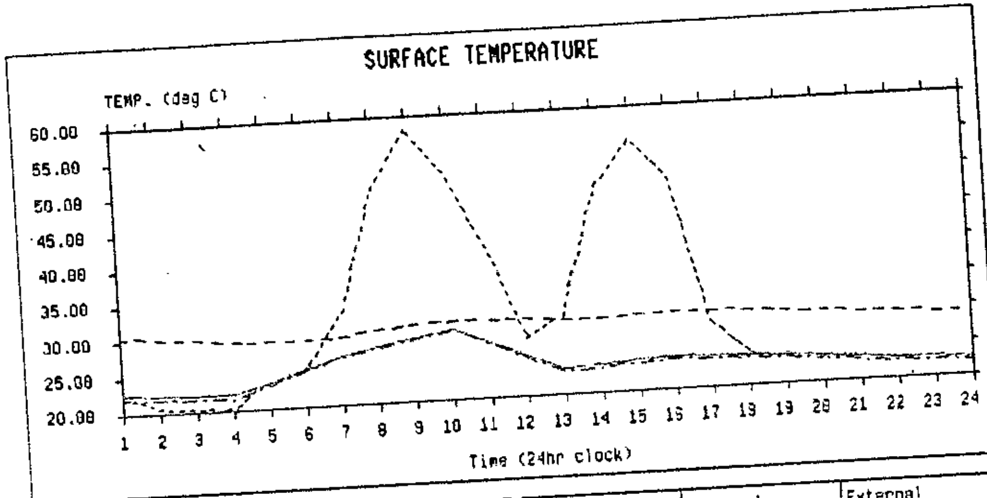
Weather: Ban_Dhaka.wfl

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	31.9	27.7
2	31.7	27.6
3	31.5	27.5
4	31.4	27.4
5	31.1	26.0
6	30.9	24.6
7	30.6	24.7
8	30.4	24.8
9	30.8	46.1
10	30.8	47.2
11	30.9	51.3
12	31.2	55.3

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
13	31.5	55.5
14	31.9	52.9
15	32.1	48.7
16	32.3	40.9
17	32.2	29.1
18	32.1	28.8
19	32.0	29.8
20	31.8	28.2
21	31.7	27.9
22	31.6	27.6
23	31.4	27.4
24	31.2	27.9

Figure 5.8.2 Surface Temperature of Roof in Test Room with Roof Insulation at 500mm (24 April, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
49	T1Room	T1Room.bdf.01	01	13:33:42	29:Mar:02		A-Tas 8.31



	Line Type
Internal Air	————
Internal Surface	– – – –
External Surface	....
External Air	–·–·–·–

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7

Ceiling

Building Feature: Exposed

Orientation: Ceiling

Area (m2): 16.38

Day 115: Thursday, Apr 25 (WEEKDAY)

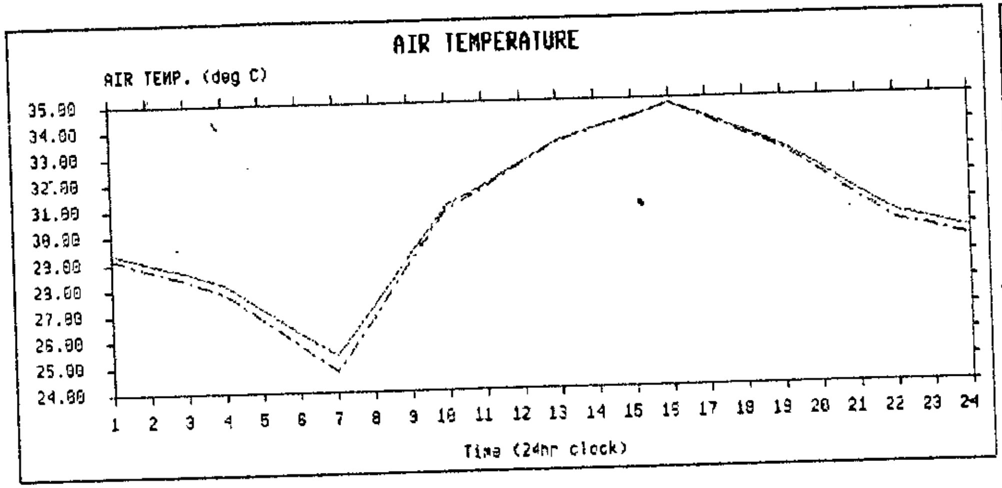
Weather: Ban_Dhaka.wfl

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	30.8	22.7
2	30.4	20.7
3	30.0	20.5
4	29.7	20.3
5	29.5	23.8
6	29.4	25.5
7	29.6	32.7
8	30.3	50.0
9	30.9	58.2
10	31.1	51.3
11	31.0	41.3
12	30.8	28.3

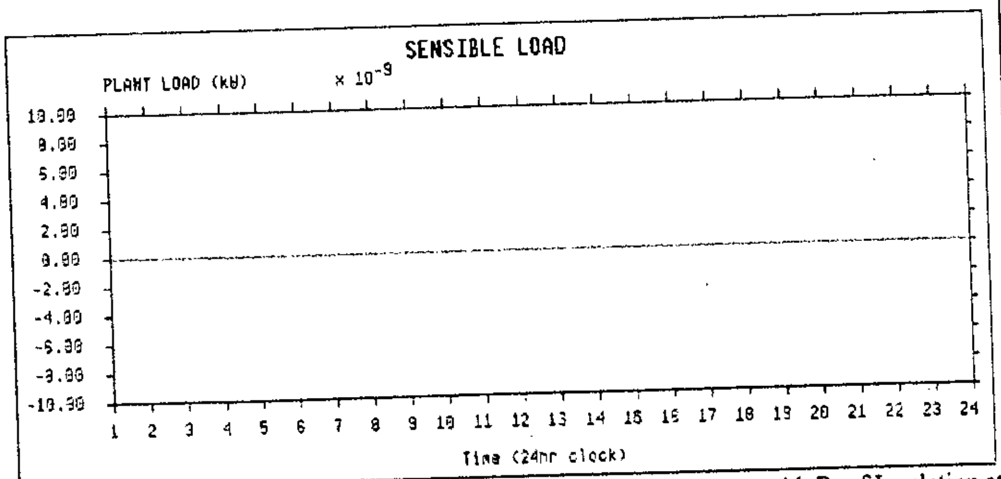
Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
13	30.5	31.3
14	30.5	48.8
15	30.6	55.4
16	30.8	49.6
17	30.8	29.2
18	30.5	24.5
19	30.3	24.2
20	30.0	23.8
21	29.7	23.4
22	29.4	23.0
23	29.2	22.8
24	28.9	22.6

Figure 5.8.3 Surface Temperature of Roof in Test Room with Roof Insulation at 500mm (25 April, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
5	T3 Room	T3.bdf.01	84	23:05:02	04:Jun:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	

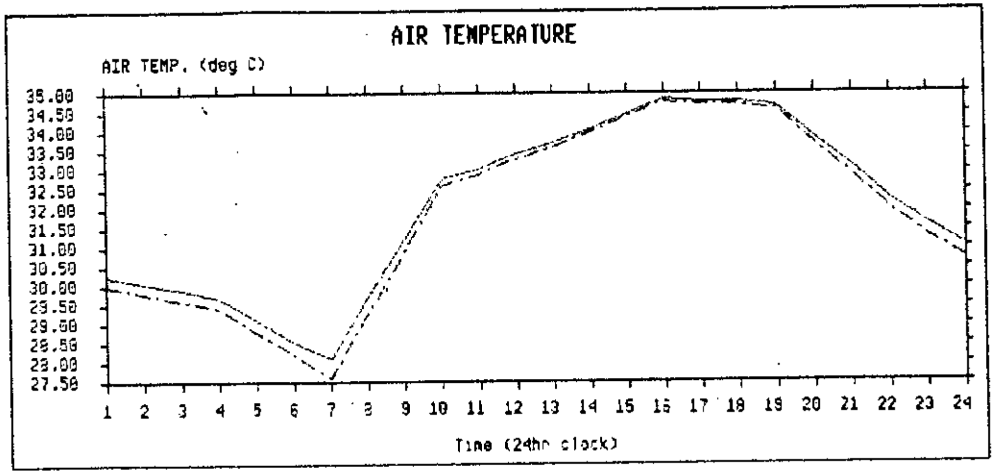


Zone	Cooling (kWh)
6 Test Room	0.00
Outside	

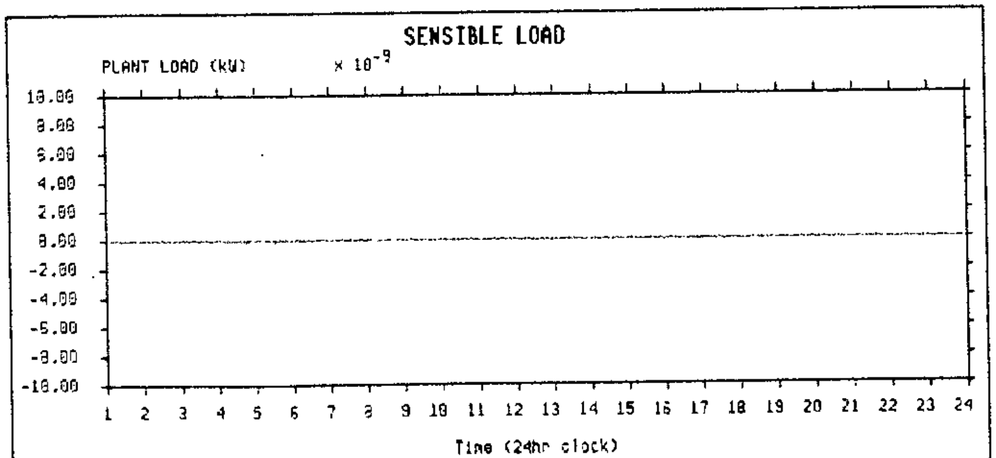
Day 132: Sunday, May 12 (SUNDAY)
Weather: Ban_Dhaka.wfl

Figure 5.9.1 Temperature Profile in Test Room with Roof Insulation at 200mm (12 May, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
15	T3 Room	T3.bdf.01	84	23:11:39	04:Jun:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	

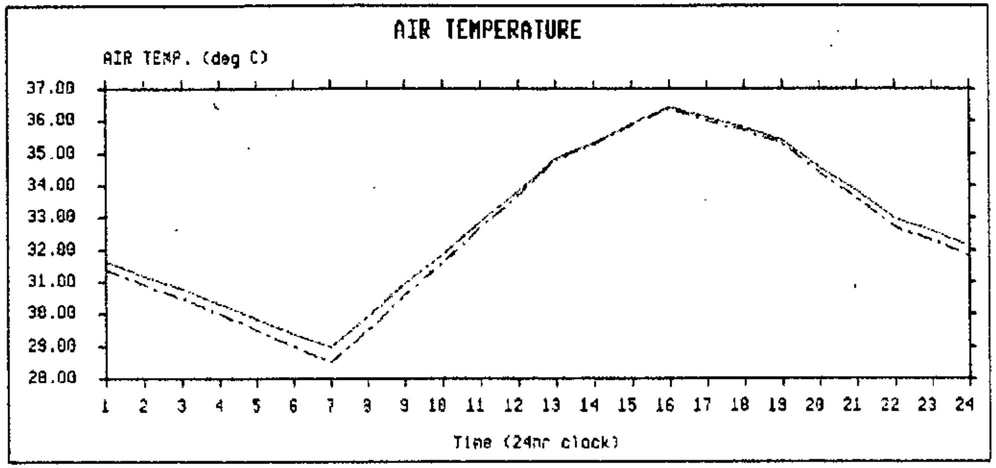


Zone	Cooling (kWh)
6 Test Room	0.00
Outside	

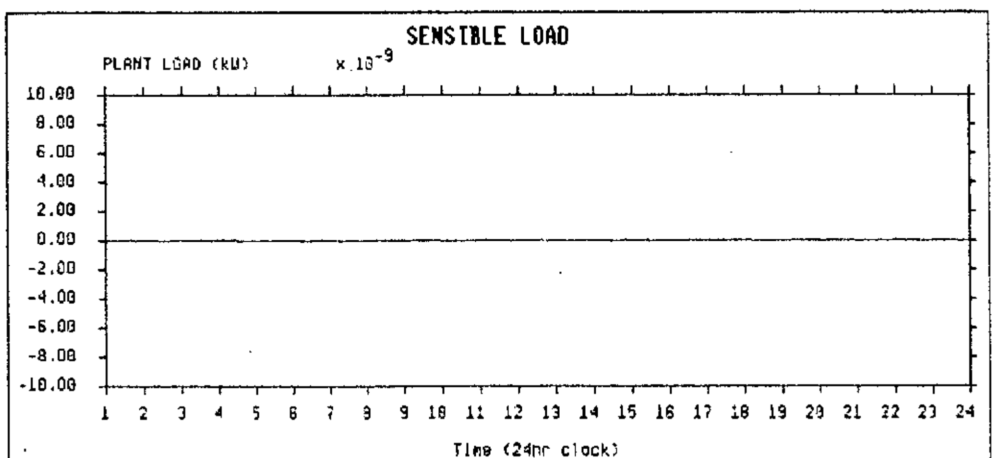
Day 133: Monday, May 13 (WEEKDAY)
Weather: Ban_Dhaka.wfl

Figure 5.9.2 Temperature Profile in Test Room with Roof Insulation at 200mm (13 May, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
25	T3 Room	T3.bdf.01	84	23:16:15	04:Jun:02		A-Tas 8.31



Zone	Heating (kWh)
6 Test Room	0.00
Outside	



Zone	Cooling (kWh)
6 Test Room	0.00
Outside	

Day 134: Tuesday, May 14 (WEEKDAY)
Weather: Ban_Dhaka.wf1

Figure 5.9.3 Temperature Profile in Test Room with Roof Insulation at 200mm (14 May, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
7	T3 Room	T3.bdf.01	84	23:06:46	04:Jun:02		A-Tas 8.31

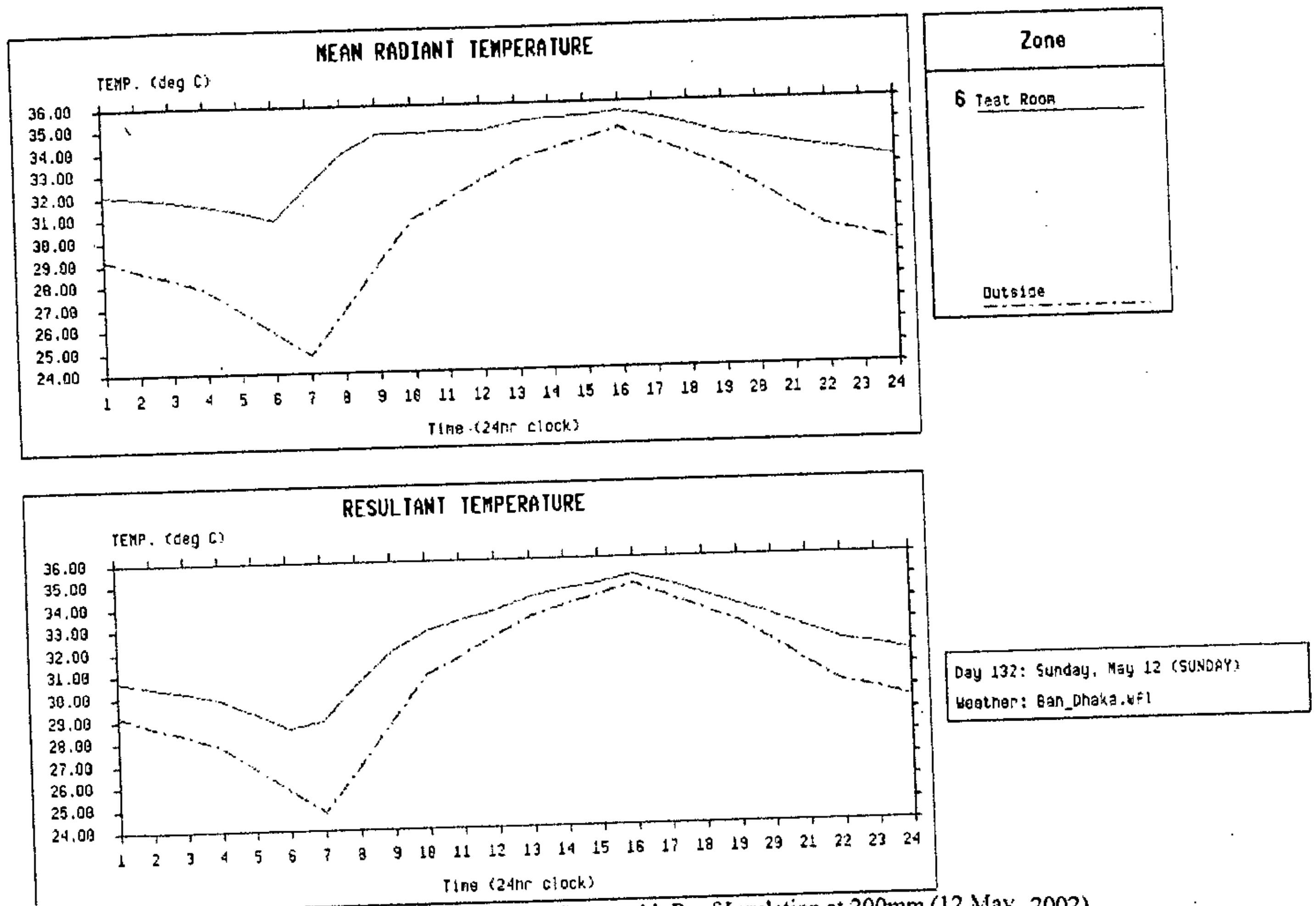


Figure 5.10.1 MRT and RT in Test Room with Roof Insulation at 200mm (12 May, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
17	T3 Room	T3.bdf.01	84	23:12:25	04:Jun:02		A-Tas 8.31

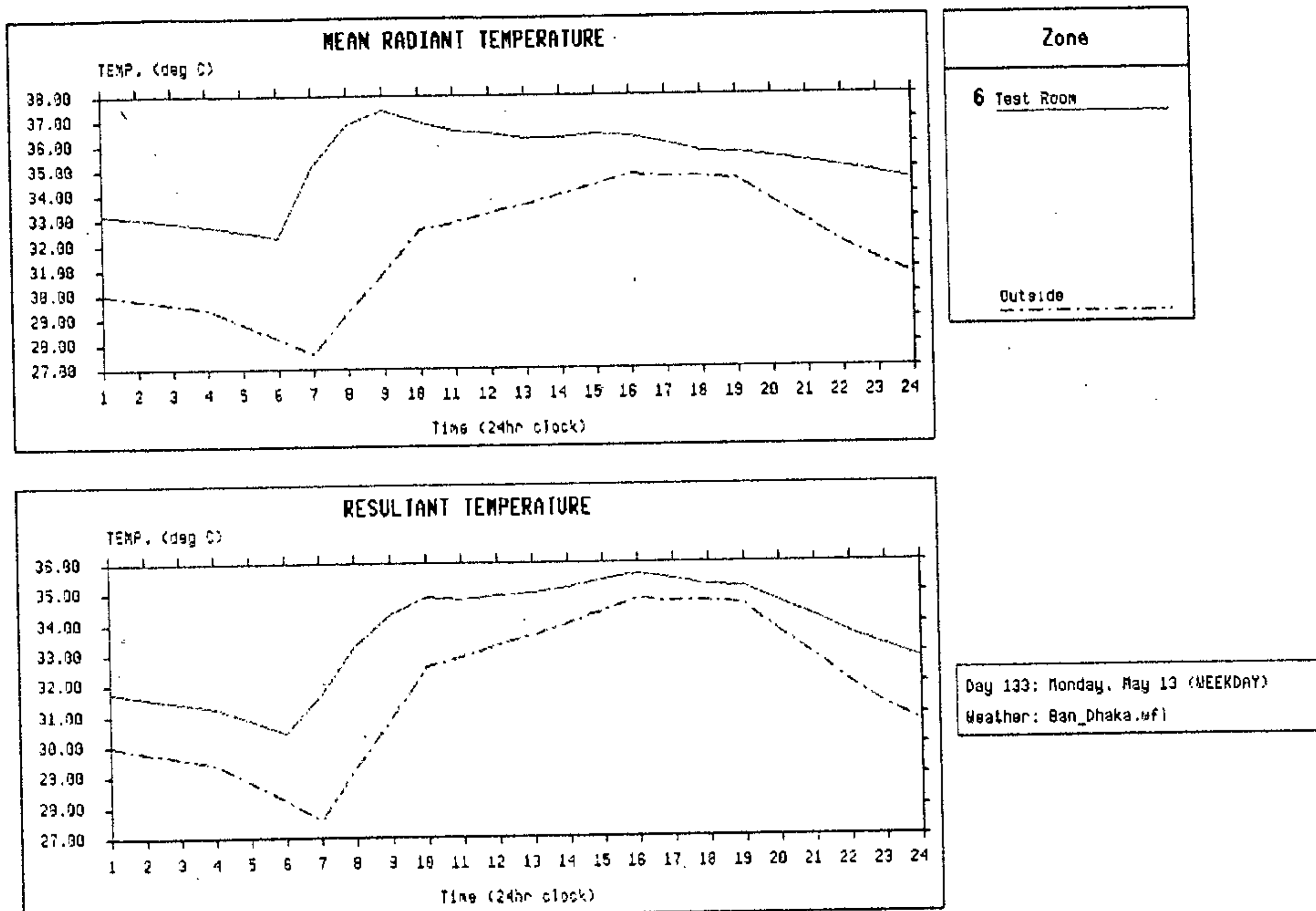


Figure 5.10.2 MRT and RT in Test Room with Roof Insulation at 200mm (13 May, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
27	T3 Room	T3.bdf.01	84	23:17:46	04:Jun:02		A-Tas 8.31

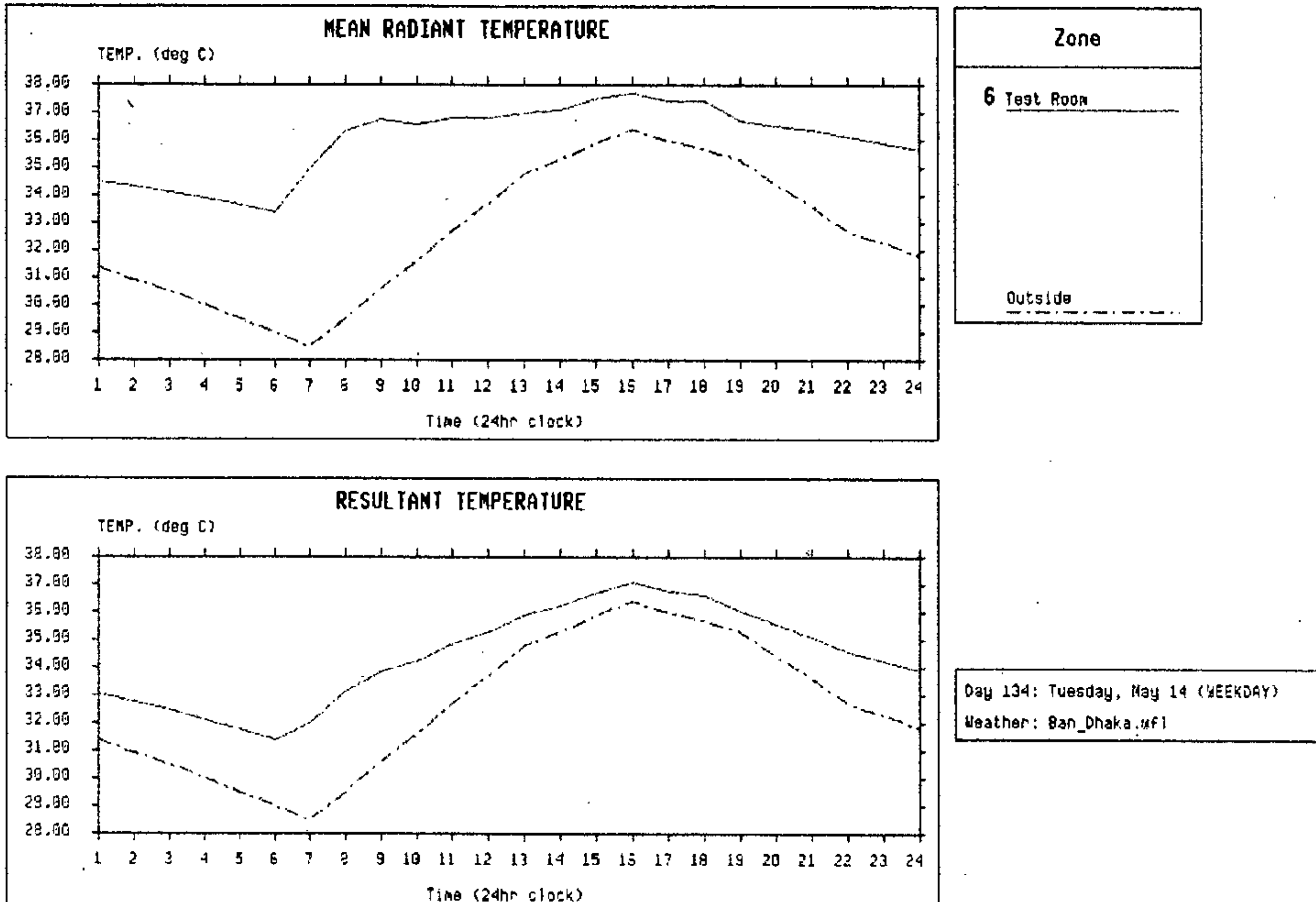
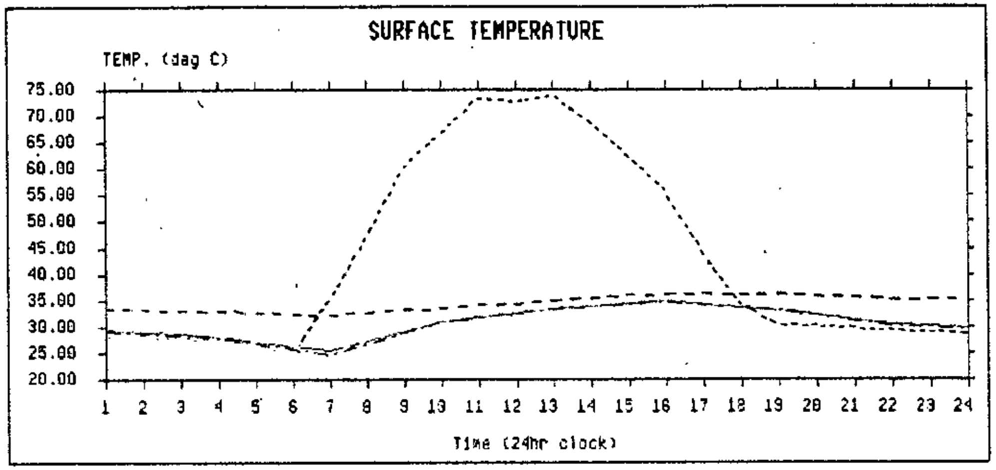


Figure 5.10.3 MRT and RT in Test Room with Roof Insulation at 200mm (14 May, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
10	T3 Room	T3.bdf.01	84	23:08:11	04:Jun:02		A-Tas 8.31



	Line Type
Internal Air	————
Internal Surface	– – – –
External Surface	·········
External Air	–·–·–·–

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)	Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	33.4	28.2	13	35.0	73.9
2	33.3	28.0	14	35.5	68.8
3	33.1	27.8	15	35.9	62.3
4	32.8	27.6	16	36.2	55.6
5	32.6	26.4	17	36.3	43.6
6	32.3	25.3	18	36.3	33.9
7	32.3	35.2	19	36.1	30.3
8	32.7	47.5	20	35.8	30.1
9	33.1	60.3	21	35.6	29.6
10	33.6	66.9	22	35.3	29.2
11	34.0	73.3	23	35.1	29.0
12	34.5	72.9	24	34.8	28.5

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7
Ceiling

Building Feature: Exposed

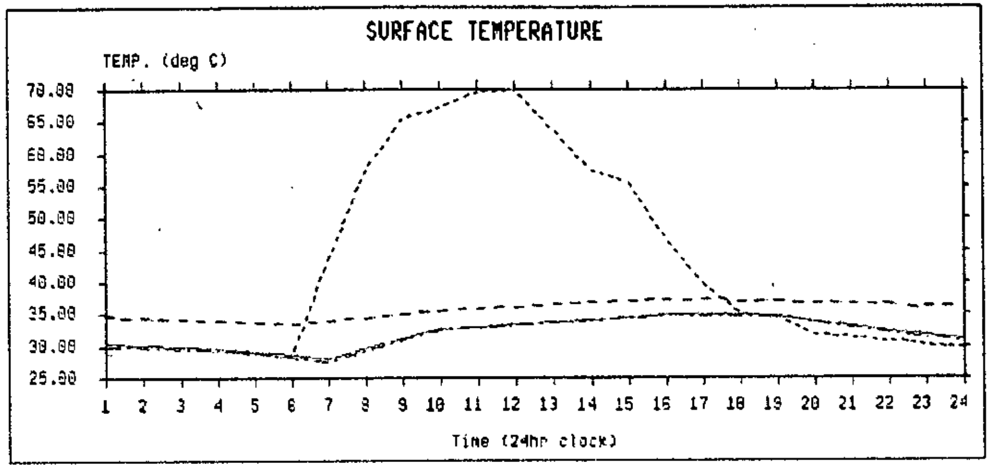
Orientation: Ceiling

Area (m2): 16.38

Day 132: Sunday, May 12 (SUNDAY)
Weather: Ban_Dhaka.wfl

Figure 5.11.1 Surface Temperature of Roof in Test Room with Roof Insulation at 200mm (12 May, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
20	T3 Room	T3.bdf.01	84	23:13:53	04:Jun:02		A-Tas 8.31



	Line Type
Internal Air	————
Internal Surface	- - - - -
External Surface	··········
External Air	-·-·-·-

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7
Ceiling

Building Feature: Exposed

Orientation: Ceiling

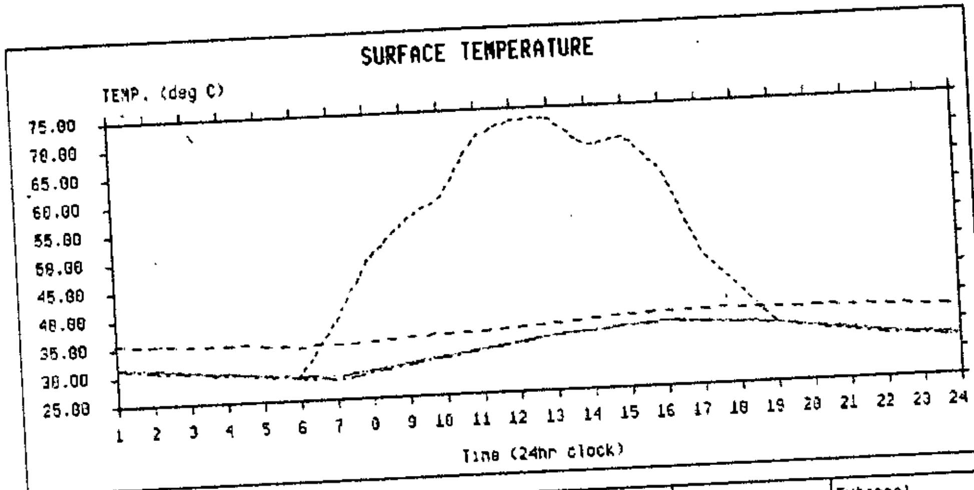
Area (m2): 16.38

Day 133: Monday, May 13 (WEEKDAY)
Weather: Ban_Dhaka.wfl

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)	Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	34.6	28.9	13	36.5	63.8
2	34.4	29.0	14	36.8	57.4
3	34.2	29.1	15	37.0	55.4
4	34.0	29.2	16	37.2	46.6
5	33.8	28.8	17	37.2	39.8
6	33.6	28.4	18	37.1	34.6
7	33.9	43.7	19	37.0	34.4
8	34.5	57.3	20	36.8	31.7
9	35.0	65.2	21	36.6	31.3
10	35.5	67.3	22	36.4	30.8
11	35.8	69.7	23	36.1	30.2
12	36.2	70.0	24	35.9	29.7

Figure 5.11.2 Surface Temperature of Roof in Test Room with Roof Insulation at 200mm (13 May, 2002)

Page	Building Name	Building Data File	Version	Time	Date	Consultant	Program
31	T3 Room	T3.bdf.01	84	23:19:23	04:Jun:02		A-Tas 8.31



	Line Type
Internal Air	
Internal Surface	
External Surface	
External Air	

LOCATION

Zone: 6. Test Room

Surface: 2

Building Element: 7

Ceiling

Building Feature: Exposed

Orientation: Ceiling

Area (m2): 16.38

Day 134: Tuesday, May 14 (WEEKDAY)

Weather: Ban_Dhaka.wfl

Time (24 hr clock)	Internal Surface Temp. (deg C)	External Surface Temp. (deg C)
1	35.7	30.9
2	35.5	30.6
3	35.3	30.3
4	35.1	30.0
5	34.8	29.6
6	34.6	29.3
7	34.7	38.5
8	35.0	49.7
9	35.4	56.1
10	35.7	60.0
11	36.1	70.4
12	36.5	72.9
13	36.9	73.2
14	37.3	67.9
15	37.8	69.2
16	38.1	63.2
17	38.3	48.5
18	38.4	42.1
19	38.3	35.5
20	38.1	34.7
21	37.9	34.0
22	37.6	33.3
23	37.4	32.3
24	37.2	31.6

Figure 5.11.3 Surface Temperature of Roof in Test Room with Roof Insulation at 200mm (14 May , 2002)

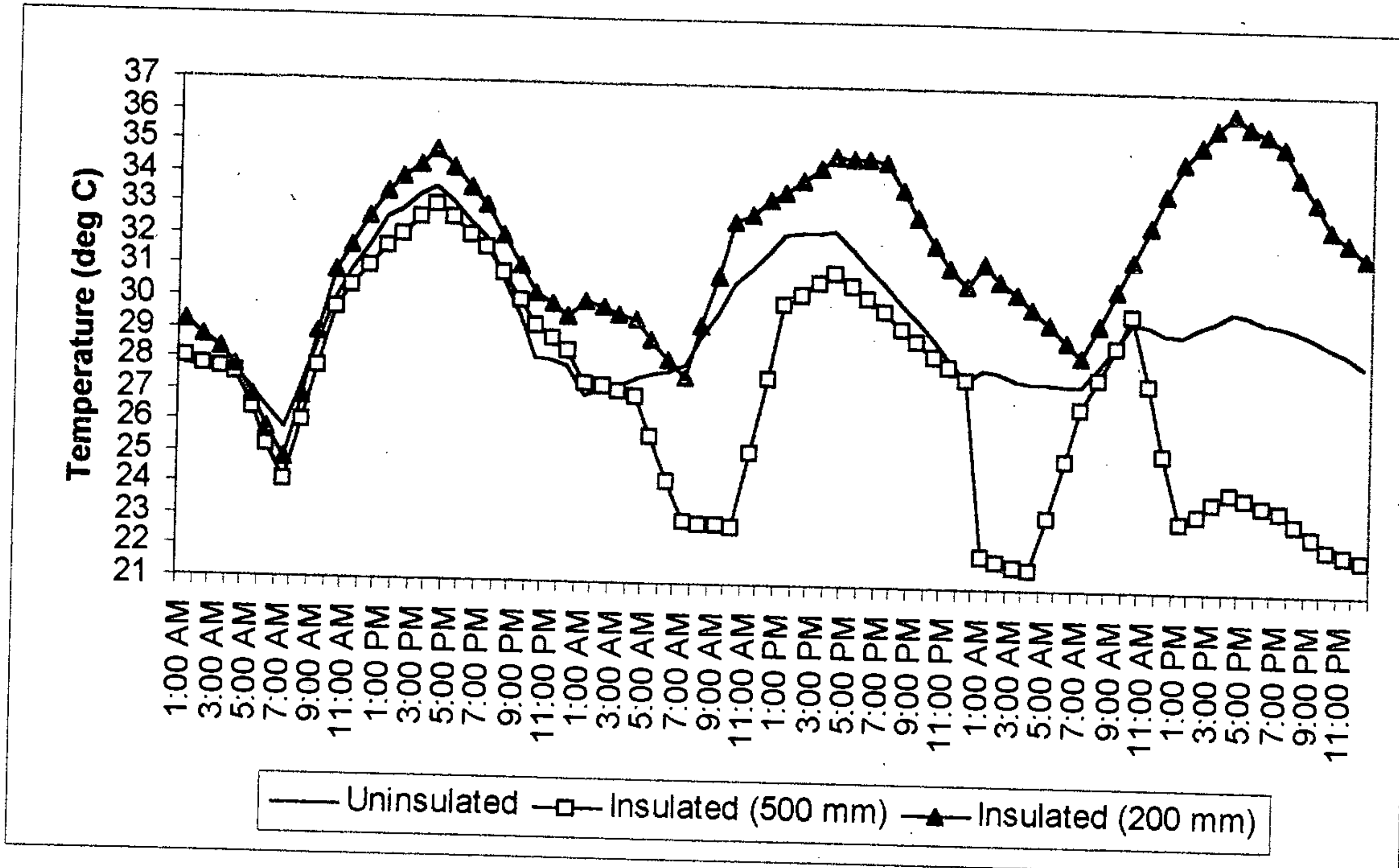


Figure 5.12 Outdoor temperature profile for the test room with uninsulated and Insulated (500 mm & 200 mm) roof for the month of June, April (500mm) and May (200mm) respectively

5.5 COMPARATIVE STUDY

In preceding sections the thermal environment in the test room with respect to uninsulated and insulated roof has been discussed individually. A comparative study is made to evaluate the performance of roof insulation hence to understand their impact on the internal environment of the test room based on the following parameters:

a) Temperature Difference (Globe Maximum vs. Indoor Maximum)

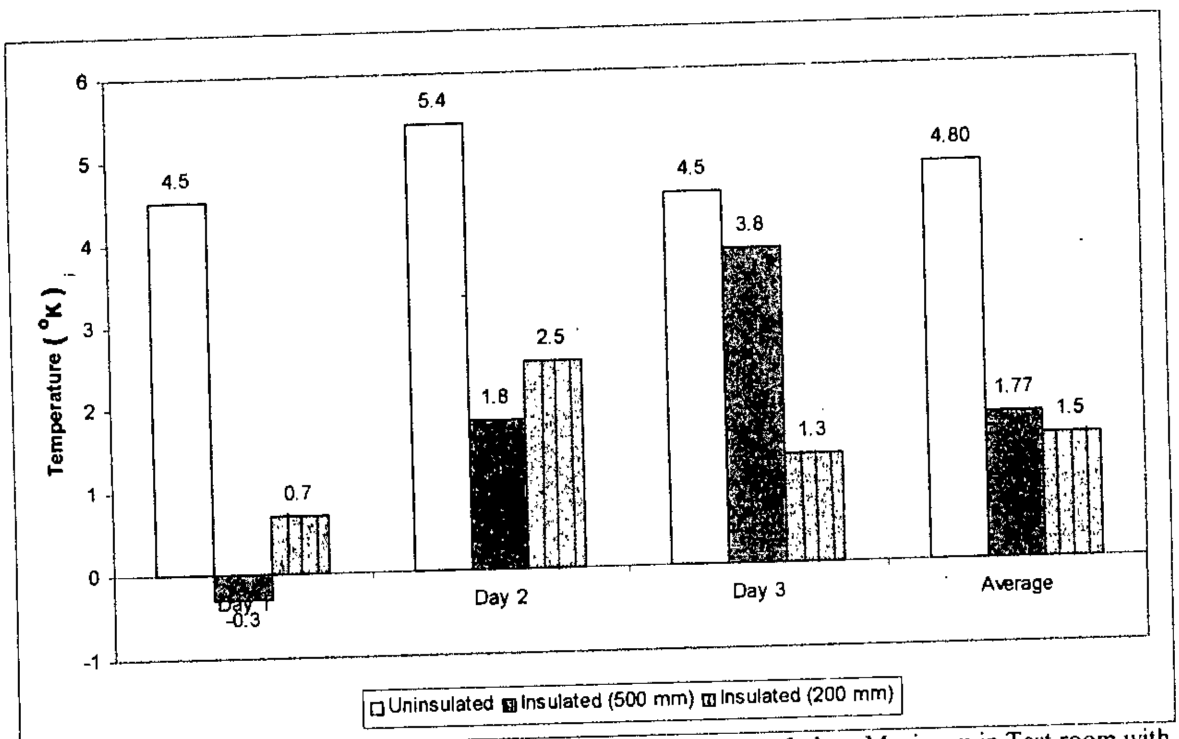


Figure 5.13 Temperature difference between daily Globe Maximum vs. Indoor Maximum in Test room with Uninsulated and Insulated roof.

Temperature difference between daily Globe maximum and Indoor maximum clearly indicates that a much higher temperature regime was observed in the test room when the roof was uninsulated. Magnitude of Globe temperature reaches over 40 °C at times. Not only the magnitude of both temperature is higher but their difference is also greater (Figure 5.13).On the other hand when the roof of test room is insulated a lower temperature prevails as compared to previous one. Actually insulation reduces the process of heat transfer from roof to the interior, it increases thermal time constant (TTC) (Givoni, 1998) of the material therefore radiant gain becomes slower and in one instance Globe temperature is lower than indoor temperature. In uninsulated case, the average temperature difference is 4.8 °K while with insulation (both at 500 and 200 mm) it is below 2 °K. All these testify that a better environmental condition exists in the test room with insulation.

b) **Temperature Difference (Indoor Maximum vs. Outdoor Maximum)**

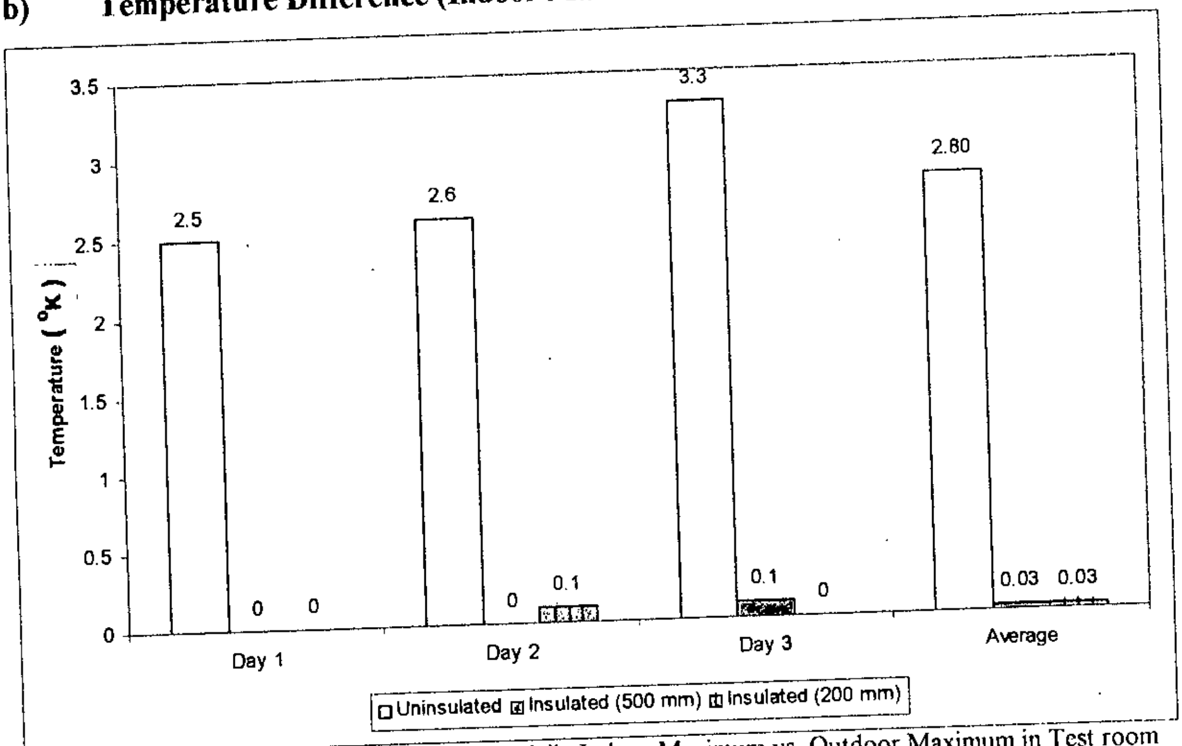


Figure 5.14 Temperature difference between daily Indoor Maximum vs. Outdoor Maximum in Test room with Uninsulated and Insulated roof.

Temperature difference between daily Indoor Max, and Outdoor Maximum is another indicator by which thermal performance of uninsulated roof and insulated roof can be judged. Figure 5.14 clearly illustrates that temperature difference between them is more pronounced with the uninsulated roof, where it is almost negligible with insulated roof. Moreover in former case indoor temperature is always much higher than the outdoor. These phenomena testifies the facts that the introduction of insulation over the roof not only reduces the indoor ambient temperature to a comfortable level but it also obstructs the main passage of heat gain (as walls and windows are uninsulated) to the interior.

c) **Temperature Attenuation**

Temperature attenuation between daily Globe Maximum and Minimum in the test room with uninsulated and insulated roof describes certain thermal conditions. Figure 5.15 illustrates temperature attenuation for 3 days for the test room with and without insulation on the roof.

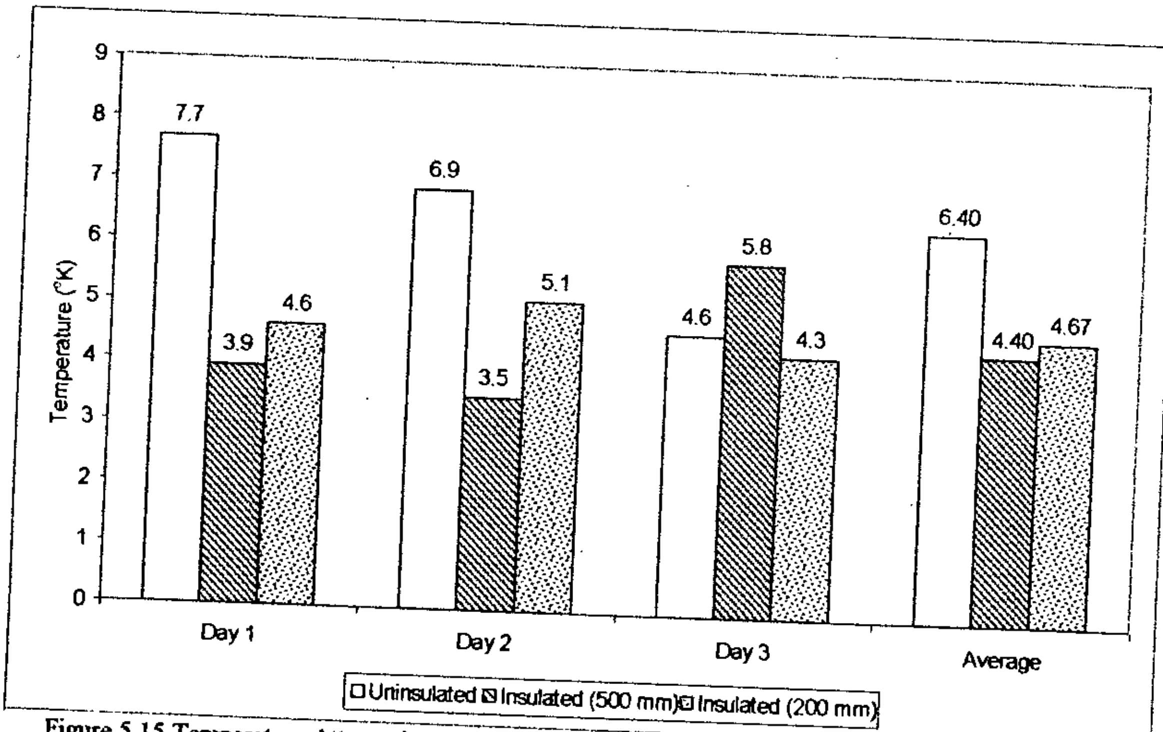


Figure 5.15 Temperature Attenuation between daily Globe Maximum and Minimum in Test room with Uninsulated and Insulated roof for June, April (500mm) and May (200mm).

Temperature attenuation in the Test room with insulation at 500mm is comparatively lower than all other conditions except for the Day 3 due to high indoor temperature. The average of Temperature attenuations is also presented; they are 6.4 °K for uninsulated roof and 4.4 °K and 4.67 °K for insulated roof at 500 and 200 mm height. It is evident that temperature fluctuation higher in uninsulated situation, while it is more stable in insulated roof situation. It is established fact that people's thermal tolerance is increased in more stable thermal condition, therefore later condition if desirable for thermal comfort.

d) Comfort Vote Analysis

Comfort Vote Analysis is based on seven-category thermal sensation scale after Bedford and ASHRAE (Mallick, 1994). It relates to the sensation of comfort as in the Bedford scale (Bedford, 1936) and borrows from the ASHRAE scale (ASHRAE, 1966) for description of outer categories.

Figure 5.16 illustrates that for the test room with uninsulated roof, there are no vote in comfortable and comfortably warm category while 36 votes in warm and 36 votes in hot category.

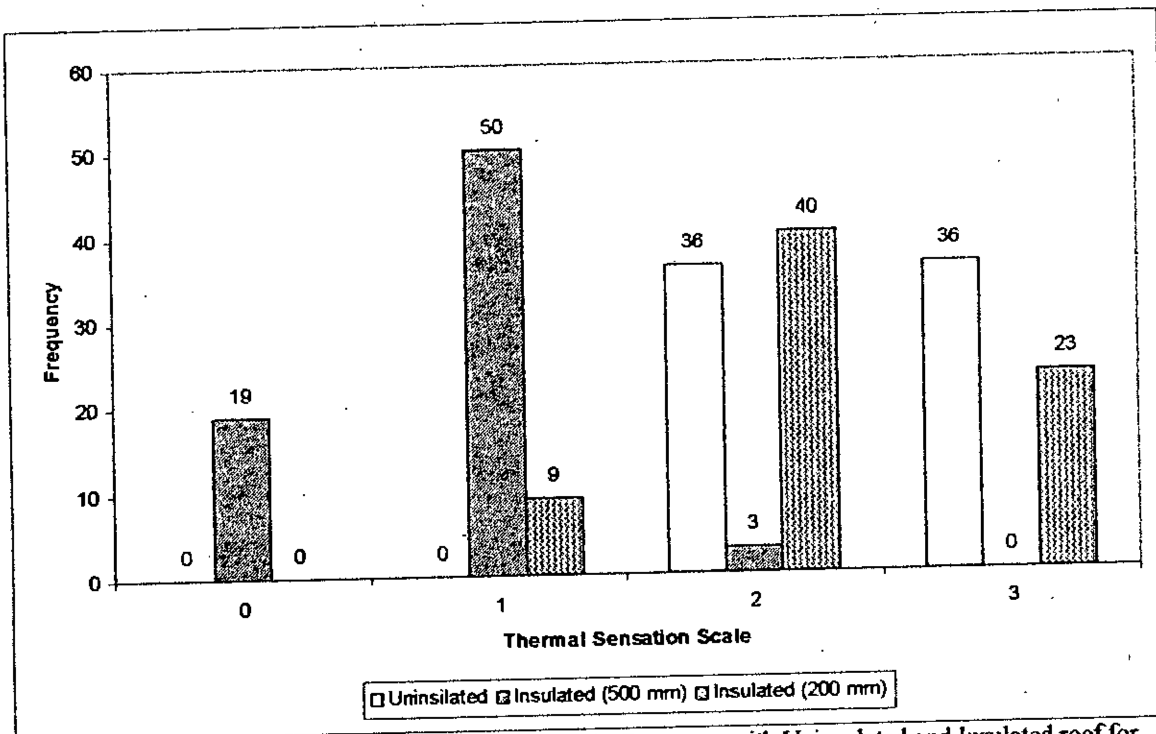


Figure 5.16 Frequency distribution of Comfort Vote in Test room with Uninsulated and Insulated roof for June, April (500mm) and May (200mm)

Test Room with insulated roof (at 500mm) receives 19 votes in comfortable, 50 votes in comfortably warm and only 3 votes in warm category, while insulated roof at 200 mm there are 40 and 23 votes in warm and hot category respectively. So it is obvious that roof with insulation gets majority of votes for comfortable category. Therefore Test Room with insulated roof exemplifies its better performance.

e) Comfort Zone Analysis

Comfort zone (see further details in chapter three) is based on indoor air temperature, relative humidity and air flow, particularly devised for summer comfort (Mallick, 1994). In still air condition, the boundary conditions for air temperature are between 24-32 °C and upper limit is increased to slightly over 34 °C with .3m/s air speed and nearly 36 °C with .45 m/s air speed. Figure 5.17 is a scatter diagram showing the relationship between Relative Humidity and Indoor Temperature of the test room with uninsulated roof. After superimposing summer comfort zone on the figure certain thermal information can be traced out. All points are concentrated between 52%-78% RH and 30-36 °C. Majority of the points are located outside the comfort zone (still air condition). However with the increase of air flow comfortable condition can be achieved.

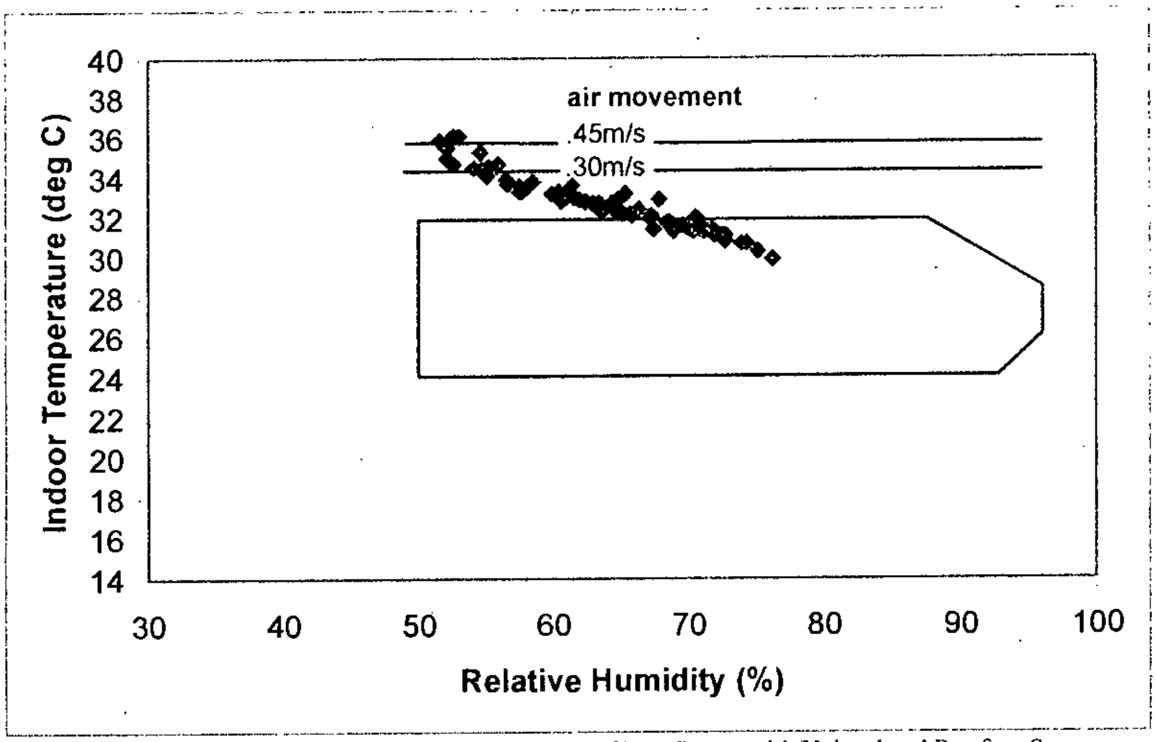


Figure 5.17 Plotting of Indoor Temperature and RH of Test Room with Uninsulated Roof on Summer Comfort Zone

In the diagram for insulated roof for the test room at 500 mm (figure 5.18), different condition occurs. Instead of concentrated points here they scatter within the comfort zone but majority of portion towards higher relative humidity (80-90%) and between 24-30 °C temperature. Some of the points are located outside the lower level of comfort zone and very few over the zone. A much better environmental condition exists here as compared to uninsulated condition.

When the height of the roof insulation is reduced to 200 mm then points scatter towards higher regime temperature. Two major concentrations are evident; one is low humidity (40- 55%) and high temperature (over 32 °C) and another is between 65-75% Relative Humidity and 29-30 °C temperature. This is a condition slightly uncomfortable than previous insulated situation (Figure 5.19).

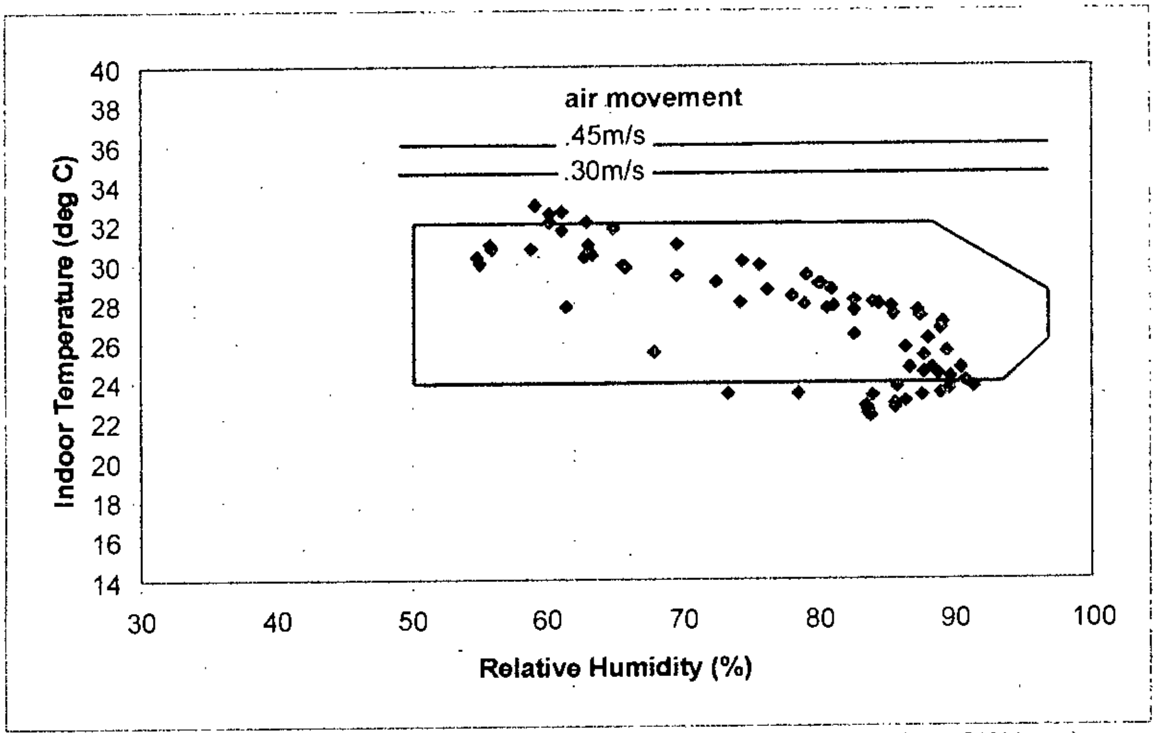


Figure 5.18 Plotting of Indoor Temperature and RH of Test Room with Insulated Roof (500 mm) on Summer Comfort Zone

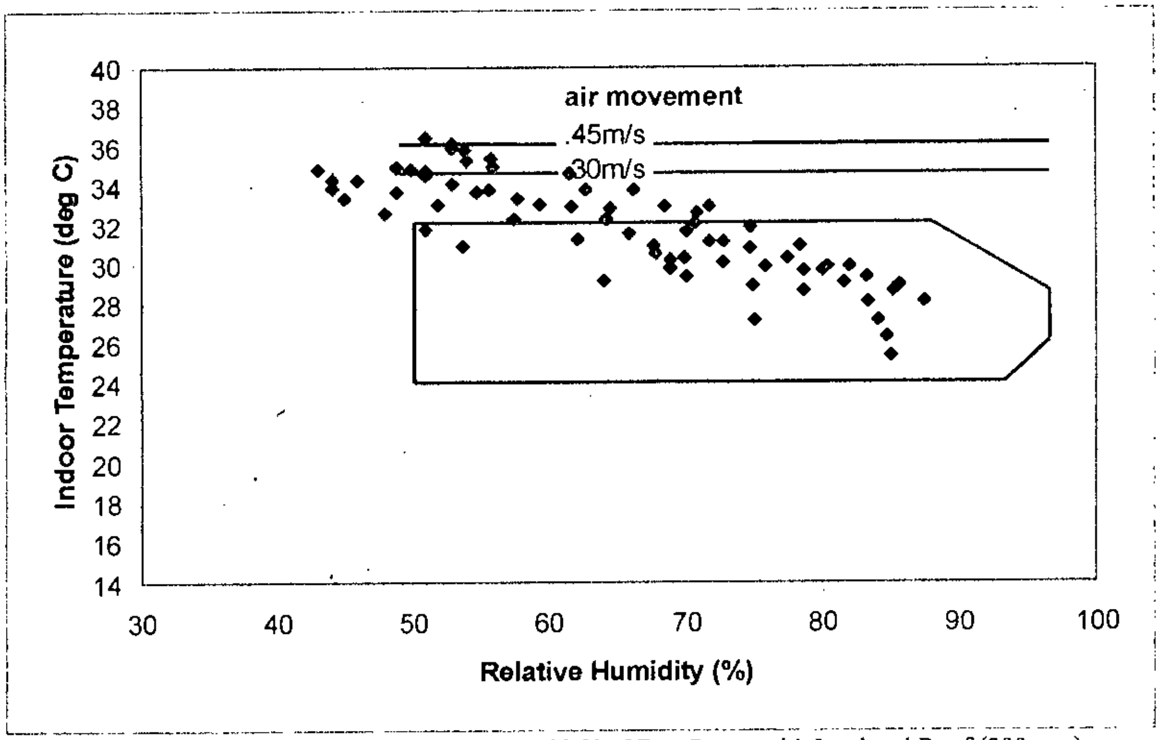


Figure 5.19 Plotting of Indoor Temperature and RH of Test Room with Insulated Roof (200 mm) on Summer Comfort Zone

5.6 CONCLUSION

The above-mentioned findings show that the thermal simulation program can be used to investigate the effect of certain changes in the internal thermal environment of the room. It is quite clear that a much better thermal condition prevails in the test room with the introduction of insulation over the roof. It actually cuts down the effect of sol-air-temperature (see chapter six for detail) on the roof, which is the main source of heat gain in Dhaka. Walls and windows (through which solar radiation penetrates inside the room) don't contribute heat gain as much as through roof. This is particularly true for single storied buildings and top floor of multistoried buildings. Moreover globe temperature is reduced with roof insulation that also brings a thermally agreeable condition. Thus the performance of the roof insulation is positively judged.

5.7 REFERENCES

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CHAPTER SIX

THERMAL PERFORMANCE OF OPERABLE ROOF INSULATION: FIELD STUDY

6.1 INTRODUCTION

Dhaka with its arrangement of urban conditions distributed over a combination of natural and man-made landscape provides abundant opportunities to study the complex and dynamic process of urban microclimates; but their effects are largely controlled by local events. Therefore it is not possible by regional climatic studies to register such transient phenomena. A study at a local scale has the potential for a broader understanding of the nature and the mechanisms of the climatic process-taking place in such conditions.

As the thesis deals with the thermal performance of operable roof insulation with special reference to Dhaka, a field study was essential to evaluate this phenomenon with a view of to establish a causal relationship between insulation and comfort. Because if a roof of high thermal mass is exposed to the sky during the night, it is cooled down by long-wave radiation, and frequently as well by convection to the cooler outdoor night air, making the roof mass into cold energy storage.

The following sections present the results of a fieldwork on thermal performance of operable roof insulation carried out in a Test Room located at Dhaka as a part of this work. The findings in this section provide the basis for the development of design guidelines in the later section of the work.

6.2 OBJECTIVE OF FIELDWORK

The fieldwork and the subsequent analysis of the field results were based on the following objectives:

- To record primary environmental data in a test room in reference to a micro-climate of the city.
- To understand the thermal performance with uninsulated roof and with operable roof insulation.
- To evaluate the indoor environments in terms of indoor comfort requirements to judge the performance of operable roof insulation for the test room.

6.3 METHODOLOGY

The fieldwork was conducted in a test room located on a top floor of a four-storied building in Dhaka. Climatic data were collected with the help of Data Loggers and sensors (details will be discussed later in this chapter) for couple of days for the test room. Prior to data collection for insulated roof a Pre-Run period continued for seven days to reduce thermal inertia of the roof. With operable insulation system data were collected at two different heights (also to study whether there is any impact of height), firstly at 450 mm above the roof which is the minimum height of parapet generally used in Dhaka and secondly at 300 mm above the roof which comes from the available width of the most economic Styrofoam panel.

Period of observation was in the months of April, May and June (2002) representing Pre-Monsoon and Monsoon period and the general climate during these periods are hot-dry and hot-wet respectively (Ahmed, 1994) (Ahmed, 1995) (Mallick, 1994). The former is characterized by low humidity and low cloud cover, high temperature, high radiation, while the later is characterized by heavy rainfall, high humidity and temperature (see chapter Two for details). These two periods are most persistent and dominant; at the same time most extreme climatic values are registered during these period. Hence addressing environmental issues of these periods in terms of studying thermal performance of operable roof insulation is of considerable importance.

Observations on environmental factors made during the fieldwork are categorized into two groups,

1. Some factors relate directly to thermal behavior, such as 'Indoor Air Temperature', 'Globe Temperature' and 'Ceiling Temperature'. These factors are directly influenced by roof insulation
2. Some factors relate to thermal impact, such as 'Roof Top Temperature'. Roof insulation is influenced by this factor.

Among other observations on environmental factors made during the fieldwork were on precipitation, radiation and cloud cover.

6.3.1 Instrumentation

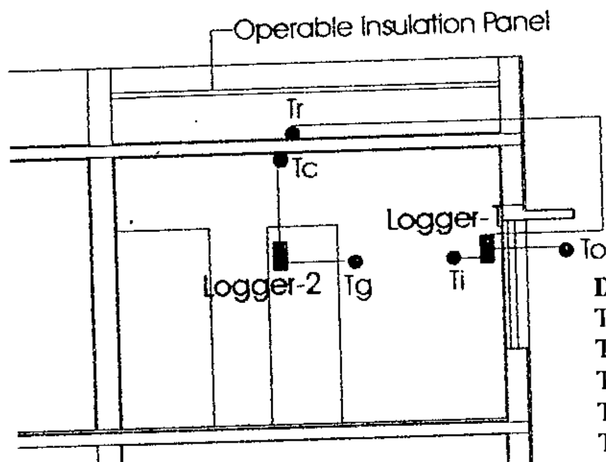
Data loggers were installed in the test room for collection of various climatic data. The remote data loggers recorded indoor air temperature and relative humidity with the help of built in sensors, while outdoor air temperature, globe temperature, ceiling temperature and roof top temperatures were recorded with the help of external sensors. Data were recorded at interval of one hour[1]. The loggers are initiated by software named BoxCar Pro 4.0 (BCP4.0-ON) supplied with the Loggers, which is also required to download data from the logger for viewing and analysis. The instruments used in field study (see Appendix 1 for detail specification) were as follows:

1. Programmable Data Logger (HOBO H08-007-02) 02 Nos.
2. External Sensor TMC6-HA 02 Nos.
3. External Sensor TMC20-HA 02 Nos.

The sensitivity of and the manufacturers calibration of the data loggers were compared with the metrological recording (under similar conditions) in Agargaon Meteorological office and found to be satisfactory.

6.3.2 Installation of Data Loggers

The data loggers were installed in the test room at two points at a height of 1.62 meter (which is average minimum man height in our context) from the floor level of the test room (Figure 6.1). Loggers were mounted on the wall with the help of hook and loop tape (Figure 6.2).



Description of External Sensors:
T_i: Indoor Temperature
T_o: Outdoor Temperature
T_g: Globe Temperature
T_c: Ceiling Temperature
T_r: Rooftop Temperature

Figure 6.1(a) Positions of Data Loggers and External Sensors in the Test Room

[1] Range of logger interval is assigned by the controlling software.

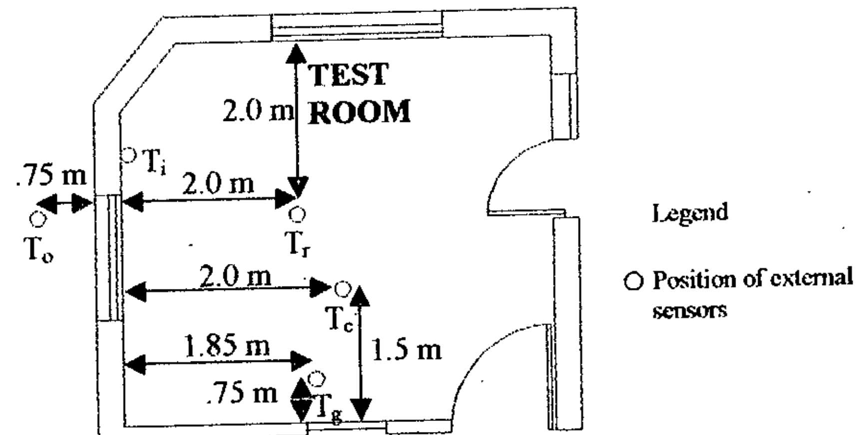


Figure 6.1(b) Positions of External Sensors in the Test Room

black (matte finish) housing a sensor inside and suspended from the wall by means of a support (Figure 6.3). (Humphrey, 1978) (Busch, 1992). External sensors were shielded from direct radiation and from rain (Figure 6.4). Sensor collecting ceiling temperature was insulated from outside to avoid radiation gain (Figure 6.5).

6.3.3 Construction and Installation of Operable Roof Insulation

Certain criteria were followed for selection of insulation material:

- Materials, which will be selected for insulation, should have low thermal conductivity, preferably between 0.03 W/m deg C (Koenigsberger et al, 1973).
- Color should be light, preferably white and should have reflective quality to reduce solar radiation penetration (Givoni, 1963) (Geiger, 1961).
- Materials should be capable of resisting weathering effect and lightweight.
- Materials should be easily available in the market and inexpensive.

Considering all above circumstances a composition of three materials were chosen to fabricate operable insulation. Main insulating material is 12.7 mm thick Styrofoam panels sandwiched between PVC sheet. Styrofoam is low conductive material, widely available and inexpensive, but can't withstand weathering effect. Therefore white colored reflective PVC sheet is used for protection, additional insulation and making the panels operable. The Transmittance value[2] (U value) of this composite membrane is 0.646 W/m^2 deg C.

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[2] $U=1/R_a$

External surface resistance	$1/f_o$		= 0.15 m^2 deg C/W (heat flow downward)
PVC (Top layer)	b/k	=0.003/0.16	= 0.01875 m^2 deg C/W
Styrofoam	b/k	=0.0127/0.01	= 1.27 m^2 deg C/W
PVC (Bottom layer)	b/k	= 0.0015/0.16	= 0.0093 m^2 deg C/W
Internal surface resistance	$1/f_i$		= 0.1 m^2 deg C/W (still air condition)
Total resistance	R_a		= 1.548 m^2 deg C/W = $U= 1/R_a$ = 0.646 W/m^2 deg C

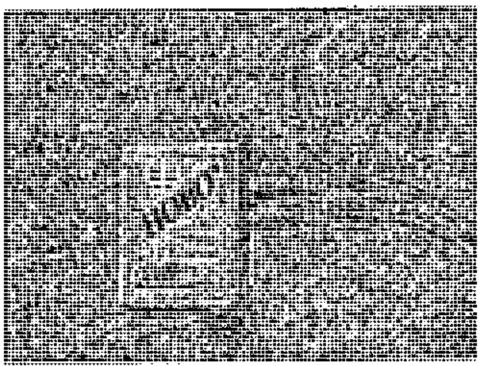


Figure 6.2 Mounting of Data Loggers on the wall by hook and loop tape

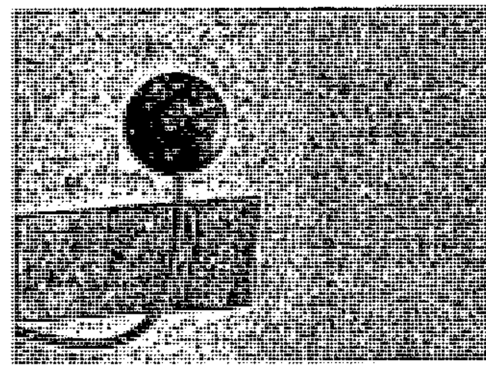


Figure 6.3 Measuring Globe temperature with the help of black painted table tennis ball

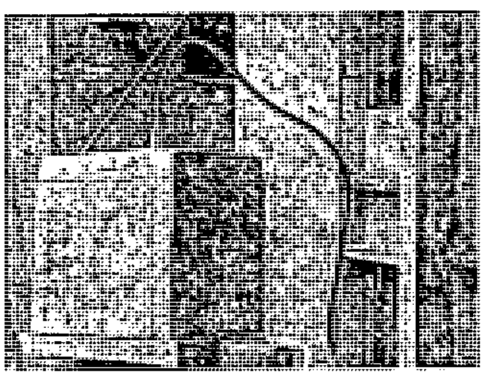


Figure 6.4 External sensor recording outdoor temp. is inserted into a Styrofoam box to protect from rain and direct radiation

Figure 6.5 External sensor recording ceiling temp. is insulated to avoid radiant gain

PVC sheet used at the top cover of Styrofoam is 3mm thick, white colored and reinforced by threads at the back, while the bottom cover is 1.5 mm thick PVC sheet. These two sheets are sewed together on three sides to form an envelope to a length similar to the length of the test room. The combined sheet is again sewed transversely at the interval of 355 mm to form a series of pockets. Styrofoam panels, which are available at 305 mm width, are inserted within the pocket to form the complete insulation (Figure 6.6 and 6.7).

Following are the accessories to install the insulation panels over the roof of the Test Room:

- Galvanized Iron Wire
- Rawl Bolt
- Angle & Eyelet
- Turn buckle & wire clamp

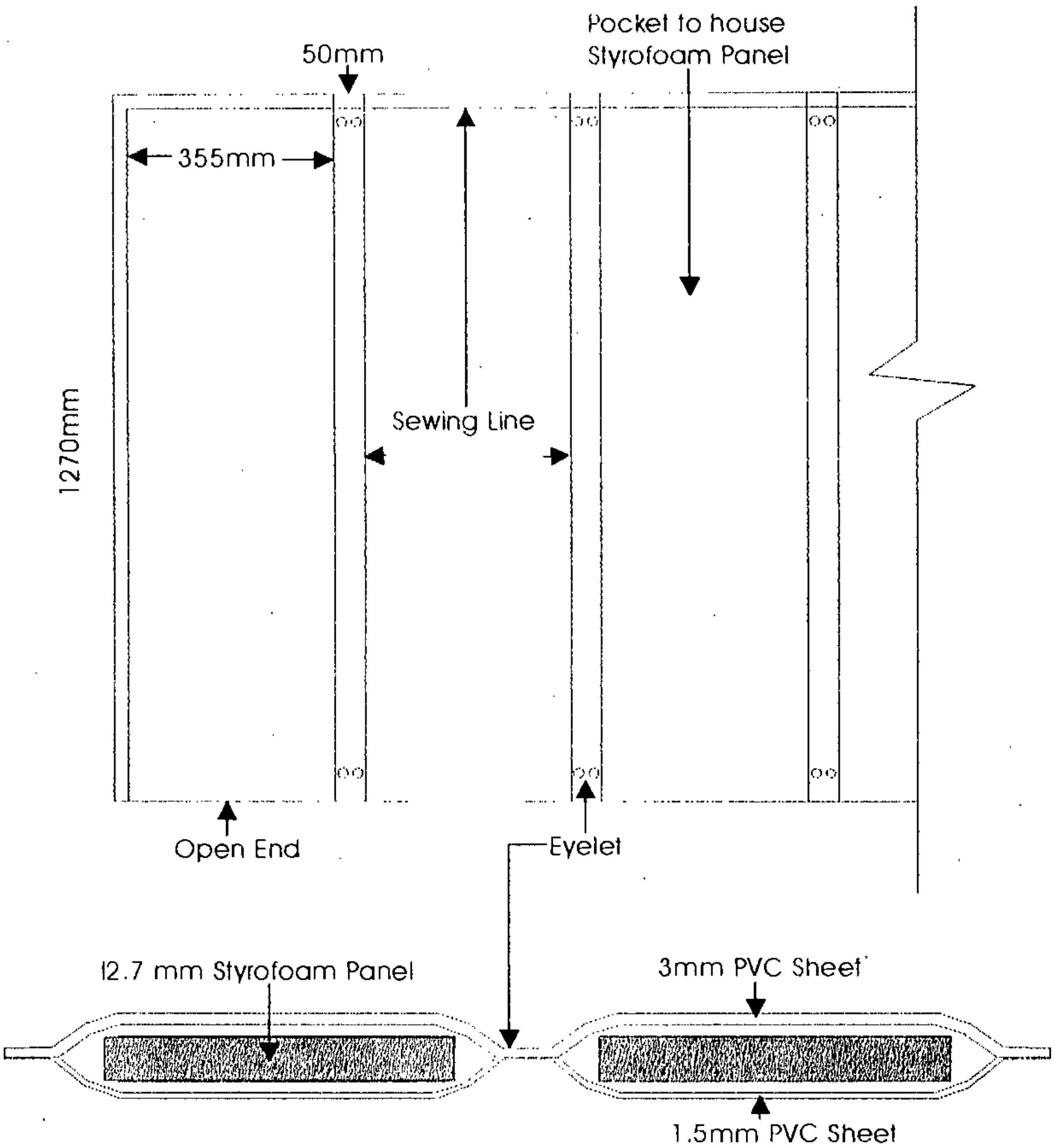


Figure 6.6 Partial Plan and Section of roof insulation membrane showing detail construction technique

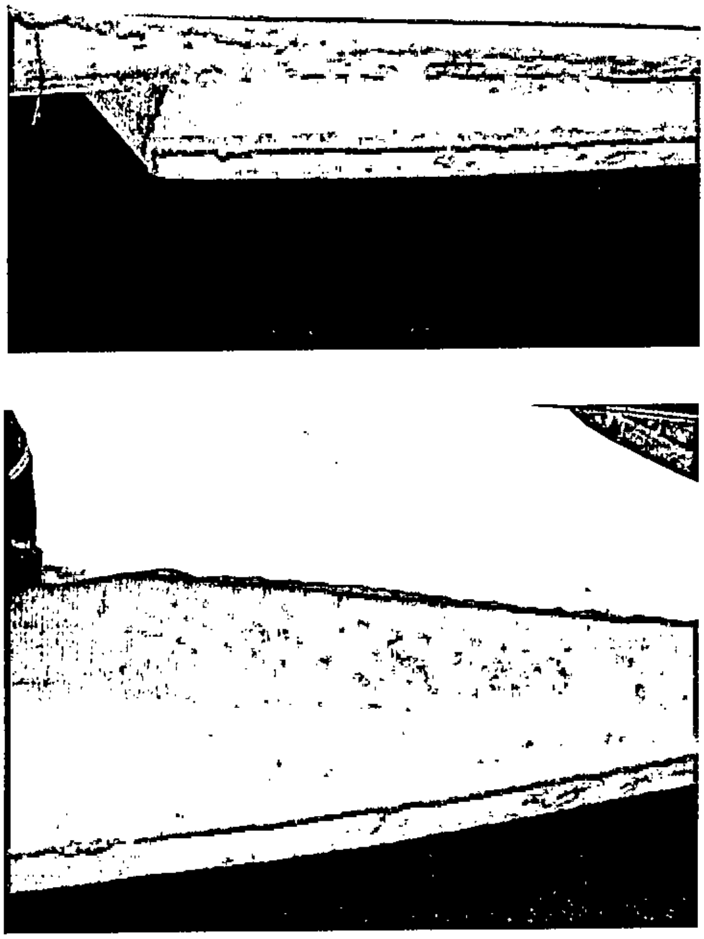


Figure 6.7 Details of the Roof Insulation

a) 12.7 mm thick Styrofoam panel is sandwiched between two layers of PVC sheet
b) Upper layer of PVC sheet (3 mm) with thread reinforcement at the back

For installation of the insulating panels, sufficient numbers of L shaped angels were fixed to east and west parapet wall with the help of Rawl bolts at 450 mm and 300 mm height (Figure 6.8). Metal eyelets were fixed to longitudinal sides of the insulating panels (Figure 6.9) and GI wire was inserted through the eyelets at two sides of each panel (Figure 6.10). End of wires were fixed to the angels on either side with the help of wire clamps and turn buckles (Figure 6.11 and Figure 6.12). Turn buckles were specially used to stretch the GI wires for smooth operation of retraction and expansion of the insulating Panels (Figure 6.13). Figure 6.14 shows the working principle of operable roof insulation for most effective use.

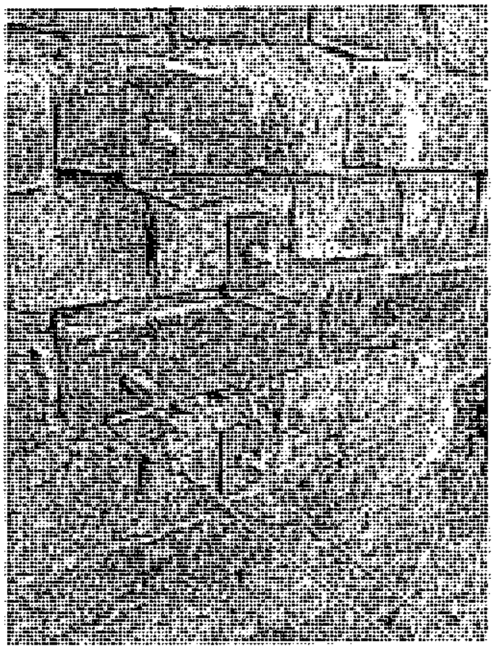


Figure 6.8 L shaped angles are fixed to wall with the help of rawl bolt

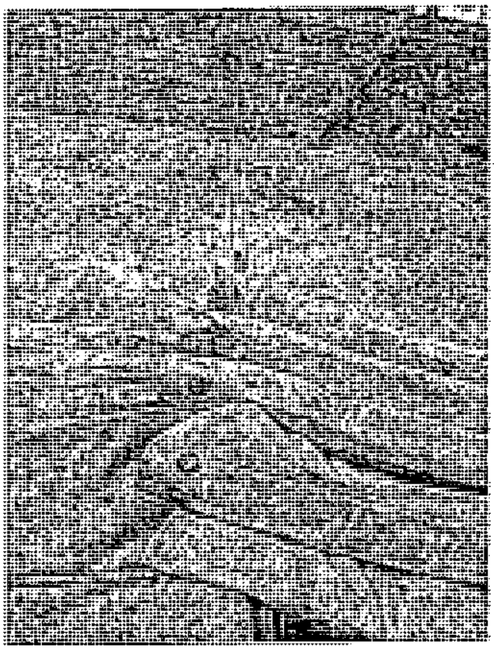


Figure 6.9 Metal cyclets helps in retracting the insulating panels

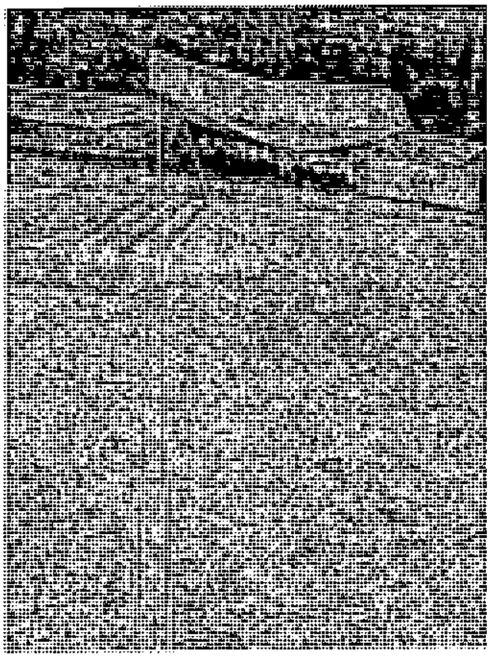


Figure 6.10 GI wires are used as channels for operable operation.

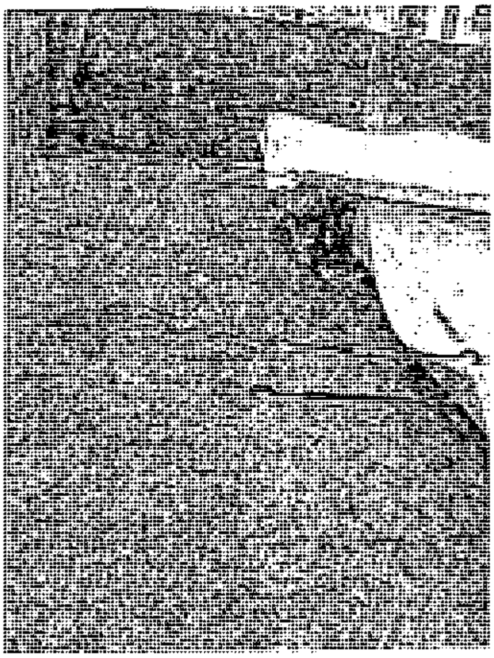
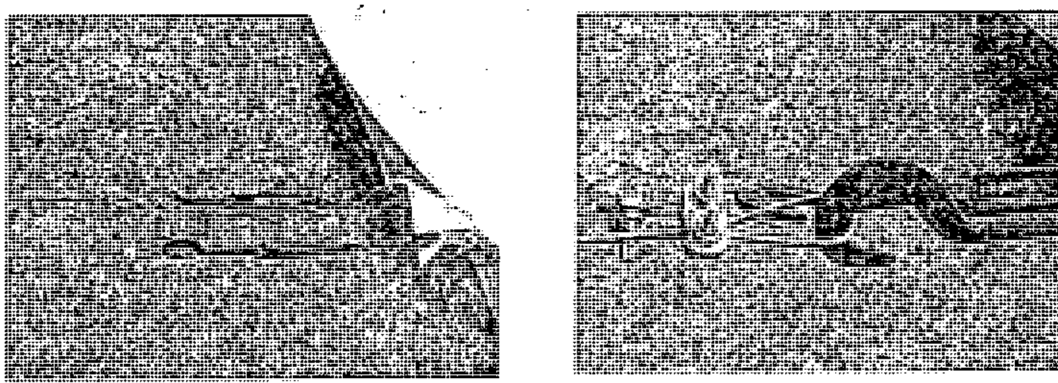
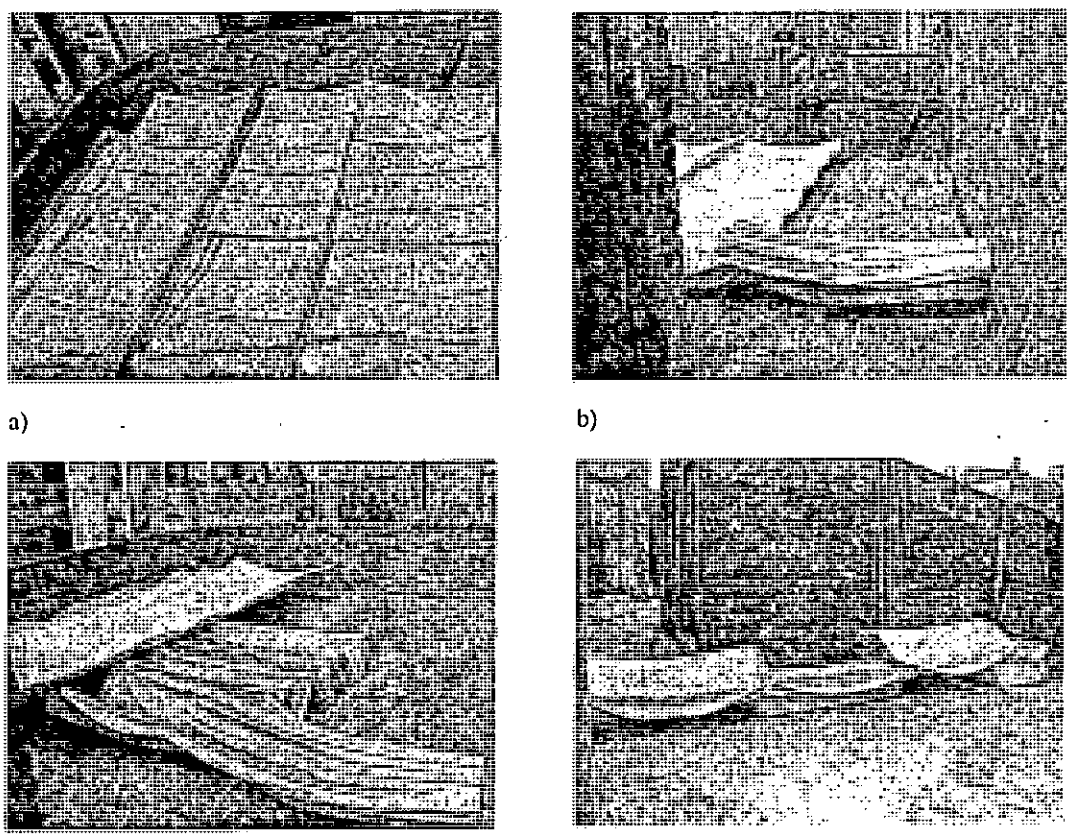


Figure 6.11 Turn buckles are assigned to stretch the insulating panels.



a) b)

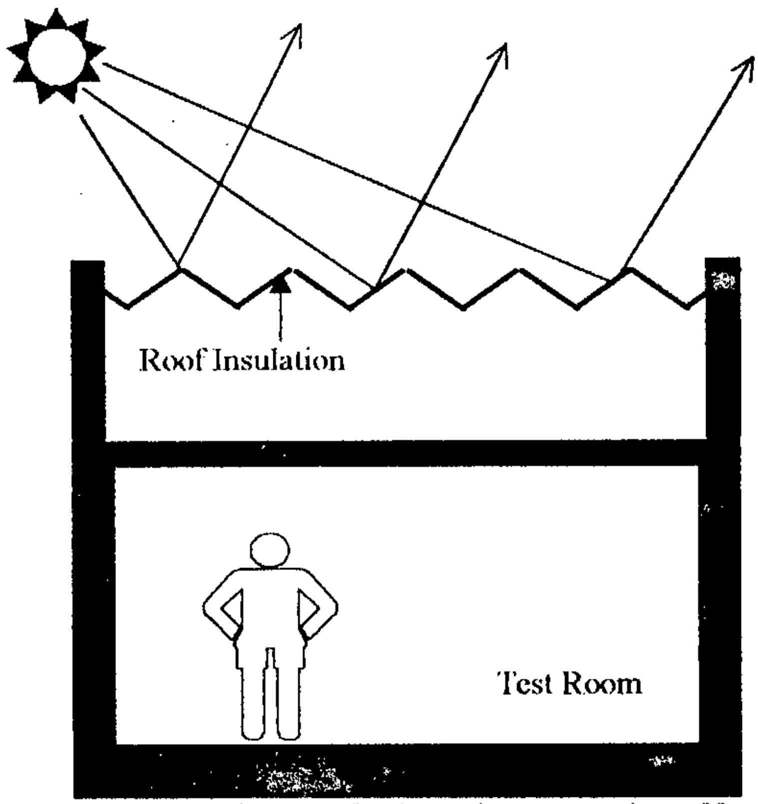
Figure 6.12 Fixing details of turn buckle and wire clamp for stretching GI wire to make insulation operable



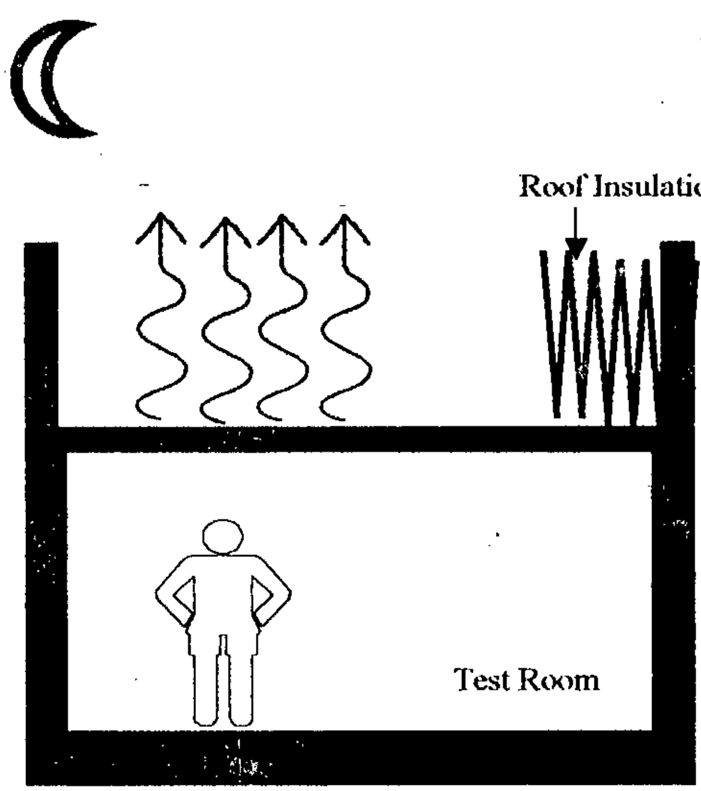
a) b) c) d)

Figure 6.13 Operable roof insulation in action

a) During daytime, roof of the test room is fully covered by insulation to protect from solar radiation
b) Retraction begins with the sun set
c) Process of retraction going on
d) Insulation panels are fully retracted and expose the roof to night sky for nocturnal cooling



a) Roof is covered by operable Insulation soon after the sunrise to protect the roof from solar radiation



b) Roof insulation is retracted after the sun set to facilitate nocturnal cooling

Figure 6.13 (e) Working Principle of Operable Roof insulation

6.3.4 Description of the Test Room

The primary criterion for selecting the test room is that,

1. It should be either single storied building or should be located at the top floor of a multistoried building in Dhaka.
2. The roof is not overshadowed by surrounding built form.

Accordingly a 4-storied building was selected at plot no 26, Monipuri Para (east side of national assembly complex). A 4.87-meter wide road passes on the east of the building. The building is situated in urban context, surrounded by walkup height residential buildings (Figure 6.15). As mentioned earlier, the test room is located at the top floor of a multistoried building occupying north-east corner. It is a bedroom measuring 4.19 m X 3.68 m. A 1.67 m wide glazed window is located on the east side while the north side window is 1.21 m wide (Figure 6.16 a). The height of the room is 2.89 m (Figure 6.16 b). The room is approached through a corridor and connected to a verandah at south-east corner. There is a toilet on west and living room on the south side of the test room. Walls of the room are constructed with .254 m brick wall, plastered and light-cream colored plastic painted in the interior. Furniture in the room consists of a double bed, a table, a wardrobe, a steel cabinet and chair. White cust in situ mosaic with brown and ash stone chips on the floor. There are four incandescent lights each with 40 –watt (occasionally used), one florescent light 40 watt (regularly used) and ceiling fan in the test room.

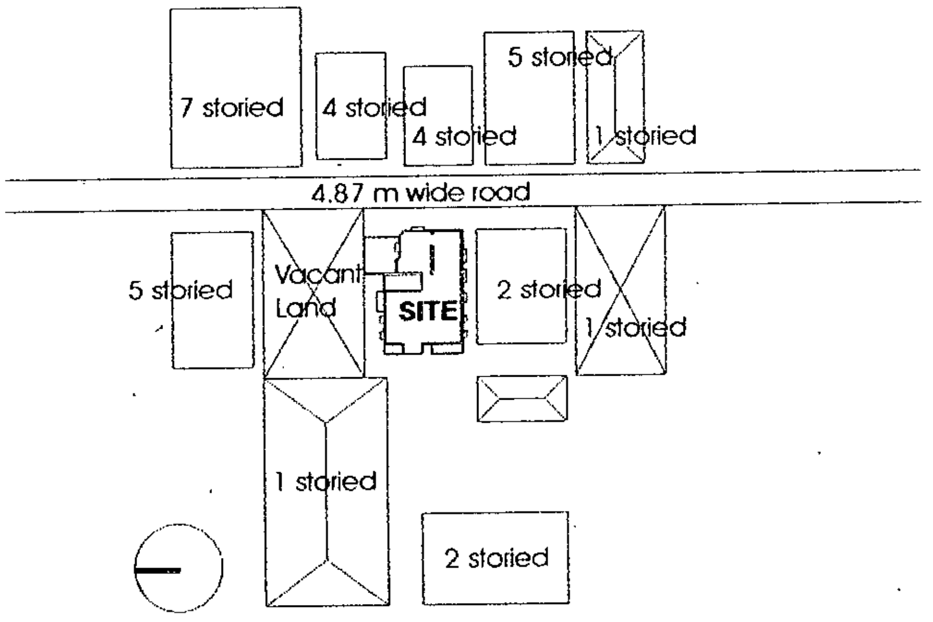


Figure 6.15 The site and the surroundings of the building in which the test room for the experiment has been selected

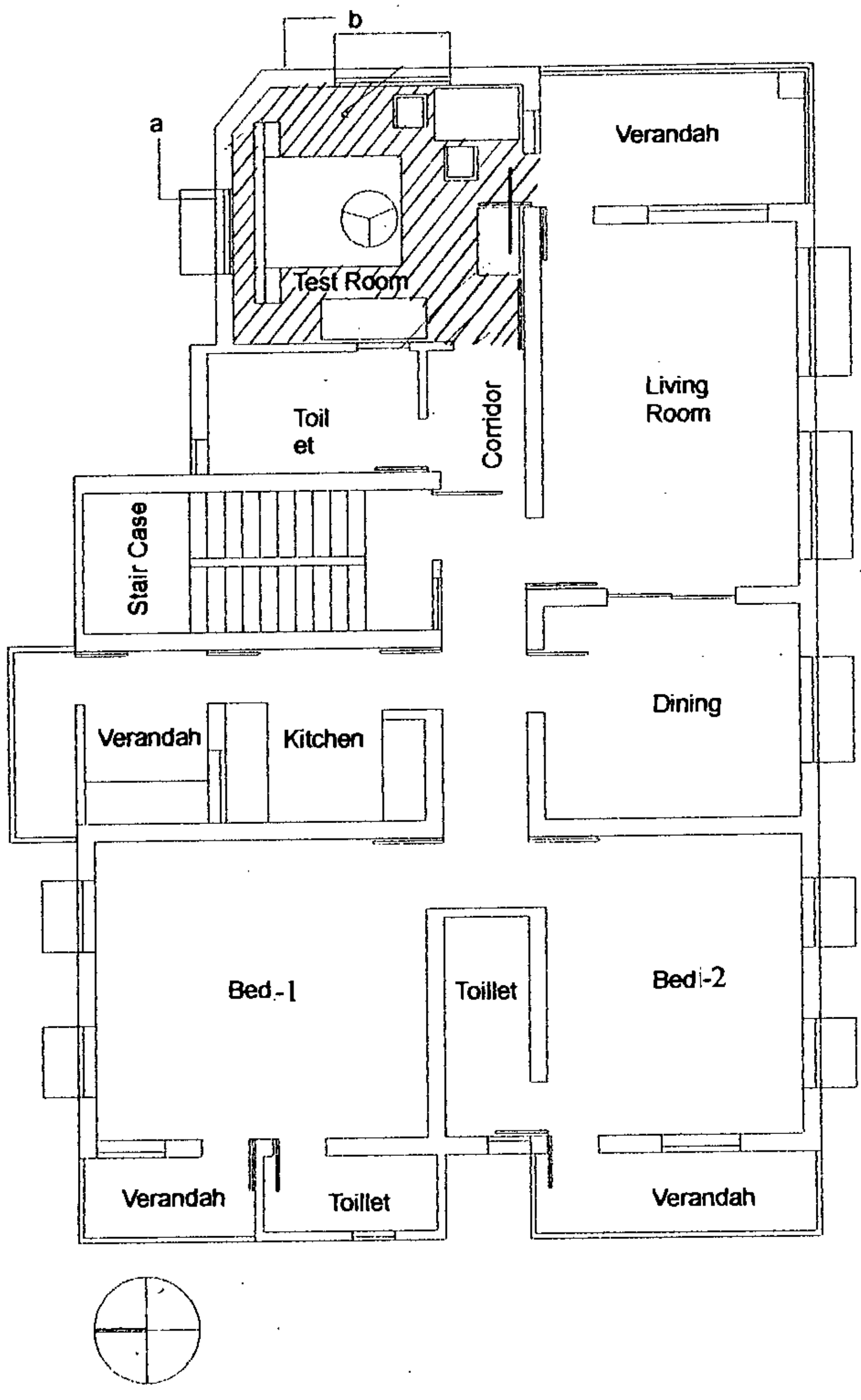


Figure 6.16(a) Floor Plan of the Test Room with its surrounding functions

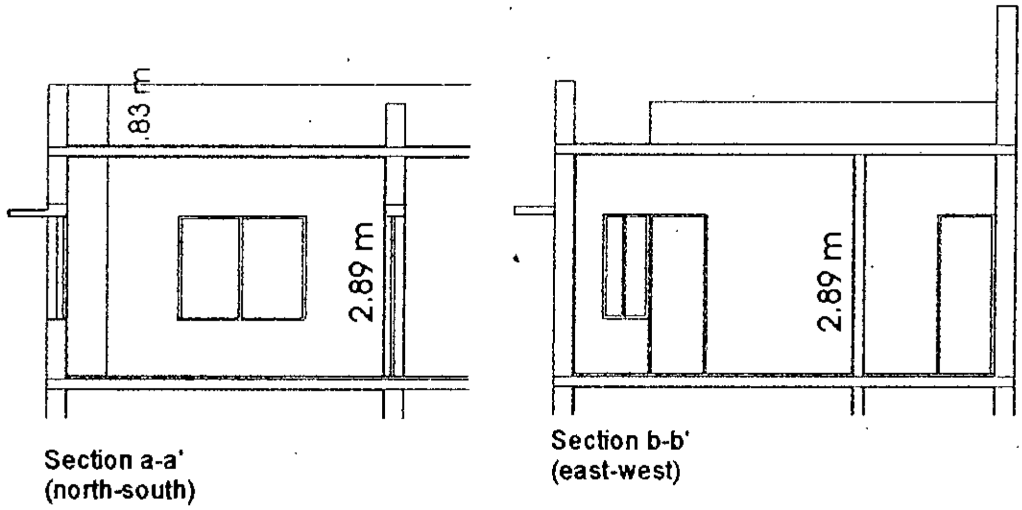


Figure 6.16 (b) Sectional detail of the test room showing north-south and east-west section

There are other considerations in selecting the test room. It is located at the north- east corner of the building while Bed-1 and Bed-2 are located on north-west and south –west corner respectively; therefore impact of solar radiation from low altitude sun affecting the west wall was thus avoided (Figure 6.16 a). During the period of field investigation further construction was made over Bed-2 and Dining but without ant parapet, for that matter there was no provision of fixing operable insulation on rooftop. Due to this construction significant amount of shadow casted on roof of Bed-1. Although Living room is surrounded by parapet wall but due to some breakage, there is more possibility of air leakage to this space. Finally shadow simulation study[3] (Figure 6.17) illustrates that roof of the test room is less affected by the parapet and other surrounding structures.

[3] Shadow simulation was generated by a software named 3D Studio MAX, Release 3.1 with the following parameters:
Latitude: 23°46'N
Longitude: 90°23'E
Date: 23 April, 12 May, 18 June (2002)
Time: 8 AM, 11 AM, 2 PM, 5 PM

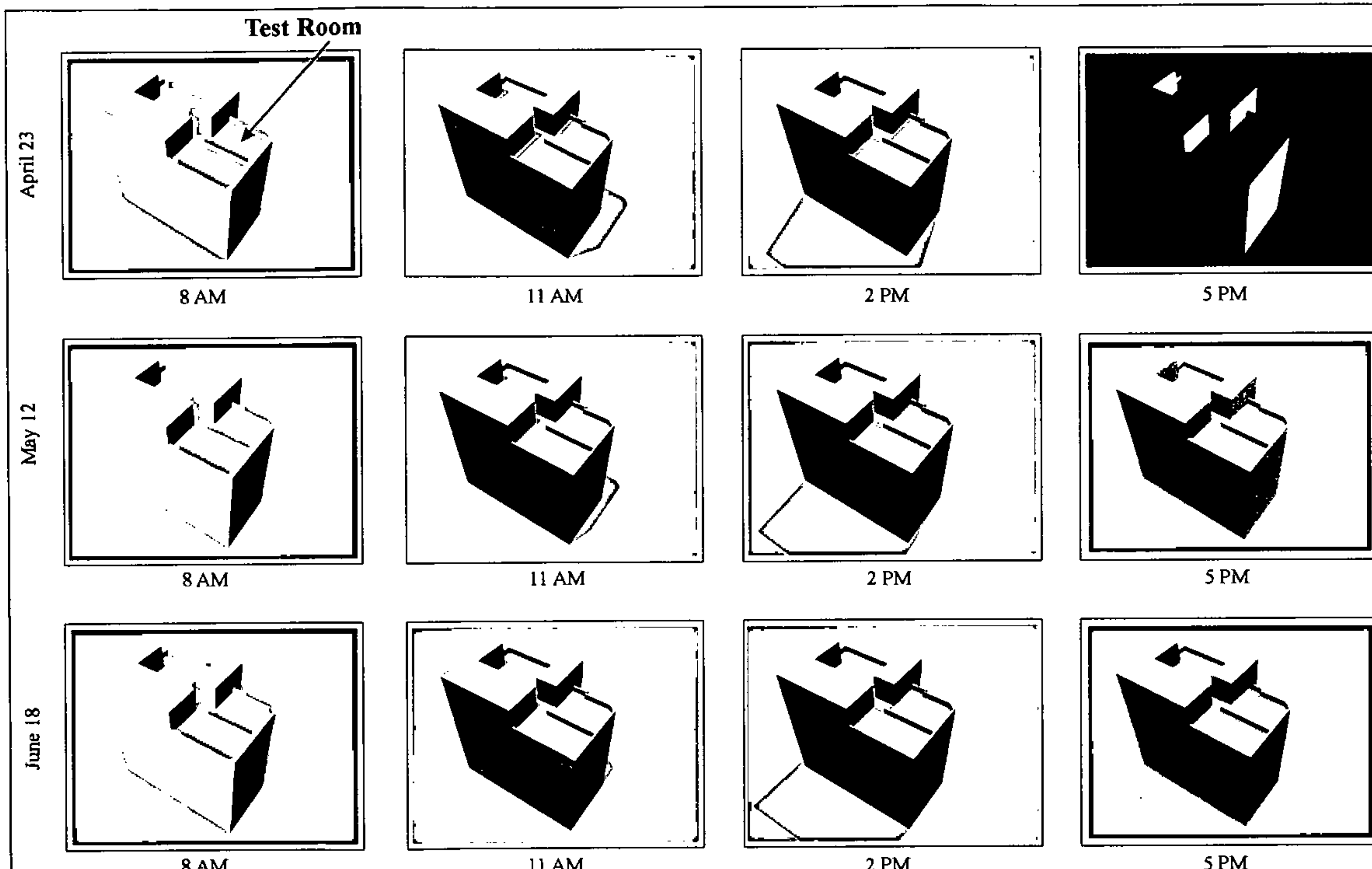


Figure 6.17 : Shadow simulation study on the roof of the Test Room
(latitude: 23°46' N, longitude: 90°23' E)

6.4 FIELD INVESTIGATION

Major findings of environmental condition of the Test room are discussed in this section to evaluate thermal performance of operable roof insulation The section is divided into following (1) Field results: Test Room without Roof Insulation (2) Field Results: Test Room with Operable Roof Insulation The intent of this investigation is to study the thermal performance of operable roof insulation Therefore uninsulated roof has been considered as a base case to which operable insulation on roof at different height can be compared. In evaluation process certain environmental criteria, which are directly influenced by roof insulation like Indoor Temperature, Globe Temperature and Ceiling Temperature in the test room, have been considered Rooftop temperature has also been taken into account as roof insulation is influenced by this factor. (see Appendix 4 for more detail).

6.4.1 Field Result: Test Room without Operable Roof Insulation

Field study was carried out in June as a base case to evaluate the performance of roof insulation. This month is selected because it represents the Monsoon or hot-wet period and characterized by high values of humidity, temperature, cloud cover and radiation. But the clearness index is low. Moreover in the context of Dhaka Monsoon is the most prolonged season (for more detail see chapter Two and appendix 5)

a) Indoor Air Temperature

Indoor temperature of a room depends on certain external factors, where roof insulation can play an important role. The significant findings of temperature data recorded from field investigation for the test room without roof insulation case are described below:

The average indoor air temperature was 31.38 °C recorded during the period of field data collection which is almost near to the upper limit of the comfort range in still air situation (Mallick, 1994). However day maximum temperature in all instances exceeded the comfort range. The diurnal difference of maximum and minimum temperature ranges between 2.05 °K to 3.66 °K Time lag varies between 6 to 7 hours (Figure 6.18). According to average temperature profile for the representative day[4] (Figure 6.20), indoor temperature ranges between 30.04 °C to 33.04 °C creating a difference of 3 °K. While the average outdoors temperature ranges between 28.05°C to 34.29 °C making a difference of above 6.24°K. The general relationship between outdoor temperature and relative humidity is that when one reaches the peak other goes to the bottom and vise versa. For majority of the hours the average indoor air temperature was over the outdoor temperature. It is evident from the logged temperature profile for the selected days that they follow almost similar trends specially the time of attainment of day maximum. The indoor temperature was in a higher regime with respect to indoor temperature with operable insulation hence the performance is inferior.

b) Globe Temperature (GT)

Globe Temperature is an average temperature of the surrounding surfaces. It includes the effect of incident solar radiation and has as great an impact as air temperature.

The average GT during the field survey was recorded as 31.57 °C, which is near to the upper limit of summer comfort zone in still air situation. The Globe maximum temperature was registered as 34.43 °C (over the comfort range) and the minimum as 29.1 °C, creating a difference of 5.33 °K. The diurnal difference of maximum and minimum GT was recorded between 2.05 °K to 4.07 °K and the time lag between them varies by 6 to 9 hours (Figure 6.19).

The representative day (Figure 6.21) illustrates that Globe Temperature ranges between 30.04 °C to 33.45 °C. It should be noted that for majority of the hours average Ceiling and Rooftop temperature was over GT. As there was no insulation on the roof there was no obstruction to the major passage of incoming heat through roof and couldn't help reducing radiant temperature to ensure thermal comfort. As a result a warm condition prevailed in the test room.

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[4] Environmental data during field investigation period is summarized within a single day (24 hour cycle) as representative day. This representative day illustrates the average values of the environmental variables considered for the evaluation of thermal performance of operable roof insulation.

c) Ceiling Temperature

As ceiling is closely related with the roof and also due to its physical positioning, any temperature fluctuation on roof directly and immediately affects ceiling temperature. A warm ceiling increases indoor temperature of the room below by convection and radiation process, therefore it is a significant factor to be considered.

According to the logged data the maximum ceiling temperature during the field investigation was recorded as 42.46 °C. The situation will be worse if air flow is introduced to achieve thermal comfort. The minimum ceiling temperature was recorded as 27.91 °C and generating a massive difference of 14.55°K. Time lag between day maximum and minimum was registered by 6 to 9 hours. The diurnal maximum and minimum temperature varies between 5.77 °K to 12.96 °K (Figure 6.19).

The representative day ceiling temperature profile (Figure 6.21) indicates a sudden rise of temperature during afternoon. Average temperature ranges between 29.10°C to 38.54 °C (generating high temperature fluctuation) causing discomfort

d) Roof Top Temperature

It is most directly related with the thermal profile of the roof insulation. The average rooftop temperature recorded during the field study was 33.81 °C, which is above the limit of the comfort temperature with still air situation. The maximum temperature was recorded as 46.4 °C while the minimum was 28.31 °C. The diurnal variation between maximum and minimum temp. ranges by 8.3 °K to 18.09 °K (temperature fluctuation is substantially high) (Figure 6.19).

The representative day temperature (Figure 6.21) shows rapid increase of temperature at noon (42.27 °C) and from evening temperature starts to fall down below ceiling temperature. Both the magnitude and fluctuation of rooftop temperature are high, as there is no roof insulation, which obviously has deep impact on the thermal environment in the test room hence the thermal comfort

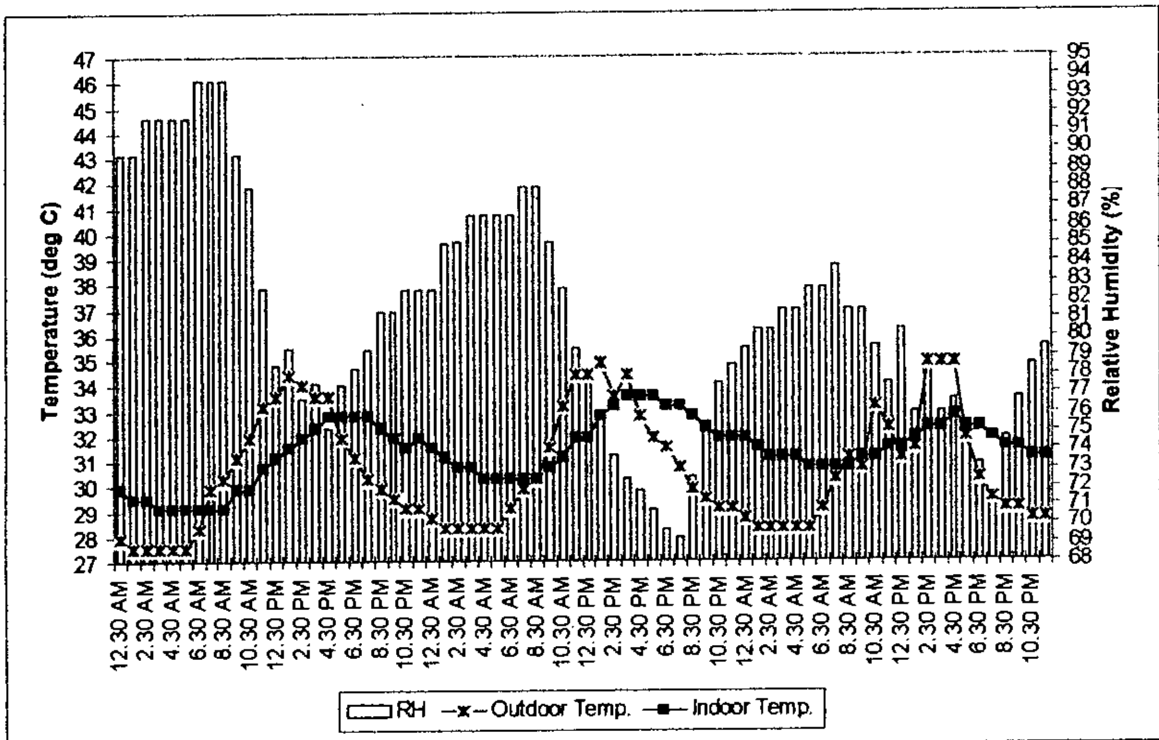

Figure 6.18 Profile of Outdoor and Indoor Air temperature and Relative Humidity of the Test Room without insulation (18-20 June, 2002)

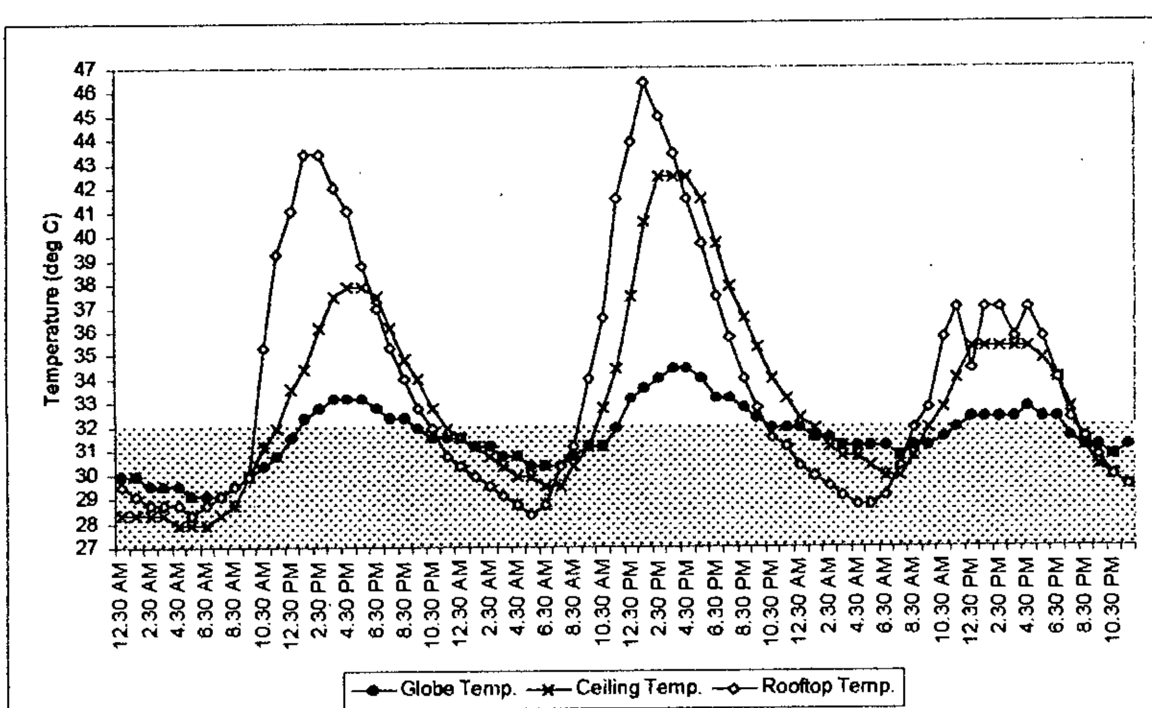

Figure 6.19 Profile of Globe, Ceiling and Rooftop temperature of the Test Room without Roof Insulation

within comfort temperature (18-20 June, 2002)

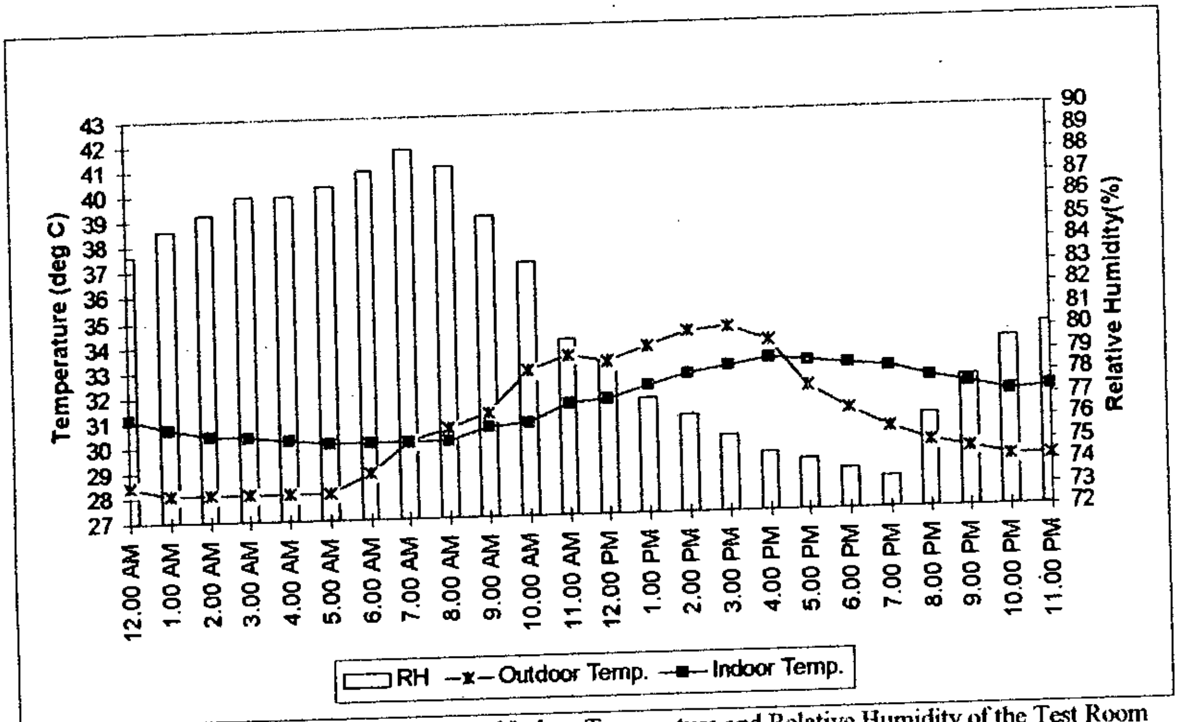

Figure 6.20 Profile of Average Outdoor and Indoor Temperature and Relative Humidity of the Test Room without roof insulation (18-20 June, 2002)

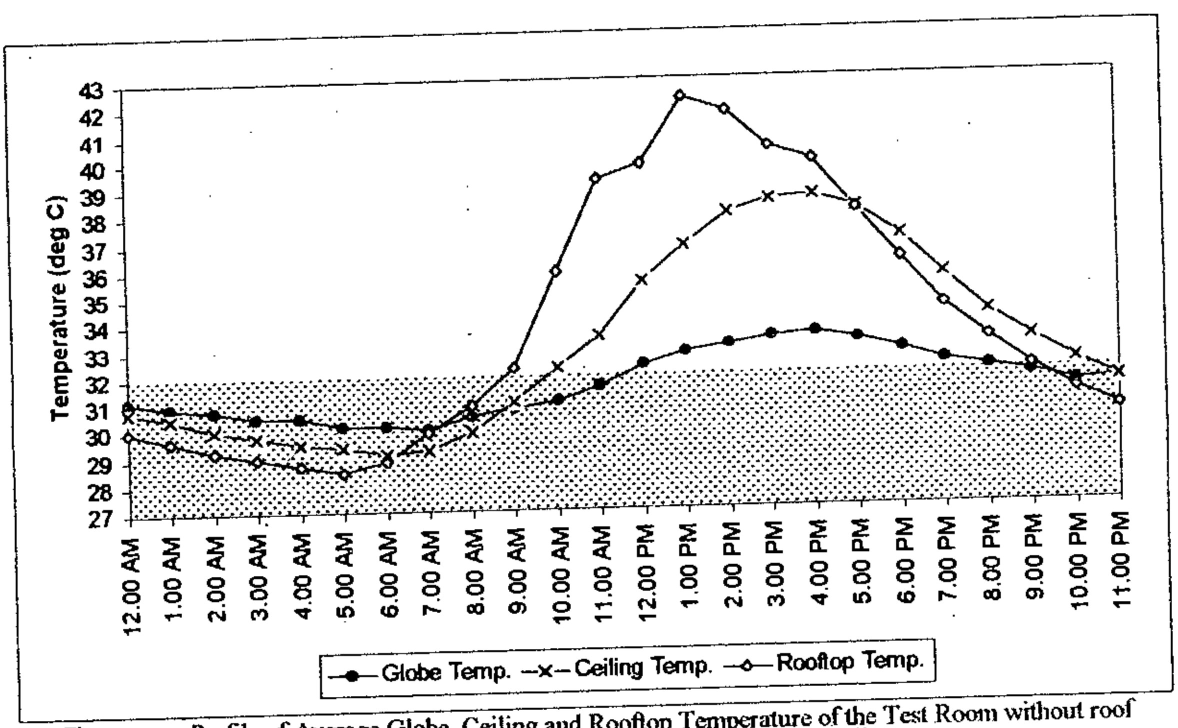

Figure 6.21 Profile of Average Globe, Ceiling and Rooftop Temperature of the Test Room without roof insulation (18-20 June, 2002)

within comfort temperature

6.4.2 Field Results: Test Room with Operable Roof Insulation

Environmental data were collected for the test room with operable insulation system at two different heights, 450mm and 300mm. The reason behind selection of former height is that it is close to the minimum height of parapet generally used in Dhaka, while the later height comes from the width of the Styrofoam panel, used as insulation material for the roof

i) At 450 mm above the Roof

Simulation study was carried out in the test room, in April, which is in hot-dry period. Temperature pattern is most pronounced during this phase. Solar radiation data and atmospheric clearness index (see chapter two) testifies that during this month high radiation influx is the major factor contributing to the high temperature in Dhaka. Thus it is the most critical among all other months of the year and chosen for investigation. Significant findings of weather data are described below:

a) Indoor Air Temperature

Indoor air temperature of a room is influenced by certain external factors. Operable roof insulation is one of those factors, which is quite capable of regulating indoor air temperature profile. The significant findings of temperature data recorded from field investigation for the test room with operable roof insulation are described below:

The average indoor air temperature was 29.97 °C recorded during the period of field data collection which is well within the comfort range in still air situation. However there was only one instance when day maximum temperature exceeded the comfort range (32.34 °C). The diurnal difference of maximum and minimum temperature ranges between 2.84 °K to 3.23 °K Time lag varies between 8 to 10 hours (Figure 6.22)

According to average temperature profile for the representative day (Figure 6.24), indoor temperature ranges between 28.57 °C to 31.39 °C creating a difference of 2.82 °K. The temperature fluctuation is minimum indicating a better thermal environment in the teat room. While the average outdoors temperature ranges between 25.05 °C to 34.29 °C making a difference of above 9 °K. The Figure 6.22 establishes a general relationship between outdoor temperature and relative humidity. When one reaches the peak other goes to the bottom and visc versa. But due to the roof insulation the indoor air temperature always in between summer comfort range with respect to no air condition. It is evident from above facts that roof insulation has profound impact on indoor temperature. It prevents the increase of temperature by reducing incoming radiation from the roof hence increase thermal comfort.

b) Globe Temperature (GT)

Globe Temperature is considered as the average temperature of the surrounding surfaces. It includes the effect of solar radiation and has great impact on comfort perception.

The average GT during the field survey was recorded as 30.15 °C, which is within summer comfort range in still air situation. The Globe maximum temperature was registered as 32.76 °C (just over the comfort range) and the minimum as 27.12 °C, creating a difference of 5.64 °K. The diurnal difference of maximum and minimum GT was recorded between 3.19oK to 3.26 °K and the time lag between them varies by 7 to 11 hours. (Figure 6.23).

The representative day summary of environmental variables (Figure 6.25) illustrates that GT ranges between 28.44 °C to 31.8 °C (within comfortable range according to Mallick, 1994) Lower temperature regime was observed in the morning hours while the higher regime during evening hours. It should be noted that average Globe, Ceiling and Rooftop temperature followed a similar pattern during observation period with maximum deviation of 2.09 °K among them. Above circumstances testify that roof insulation has influence on GT as it obstructs the major passage of incoming heat through roof and help reducing radiant temperature to ensure thermal comfort.

c) Ceiling Temperature

Due to the position, there is a close relationship between ceiling and roof. Any temperature fluctuation on the rooftop eventually affects the ceiling temperature.

According to the logged data the maximum ceiling temperature during the field investigation was recorded as 32.76 °C. The minimum ceiling temperature was recorded as 24.79 °C; thus creating a difference of 7.97 °K. Time lag between day maximum and minimum was registered by 9 to 10 hours. The diurnal maximum and minimum temperature varies between 3.91 ° K to 5.24 °K (Figure 6.23).

The representative day ceiling temperature profile (Figure 6.25) indicates it almost followed the same track as Rooftop temperature and ranges between 26.48 °C to 31.13 °C (generating moderate temperature fluctuation), which is again within summer comfort zone. It is obvious from the all above facts that roof insulation has profound bearing on ceiling temperature.

d) Roof Top Temperature

Rooftop temperature is most directly influenced by operable roof insulation. The average rooftop temperature recorded during the field study was 28.91 °C, which is almost in the mid limit of the comfort temperature with still air situation. The maximum temperature was recorded as 32.34 °C while the minimum was 24.79 °C. The diurnal variation between maximum and minimum temp. ranges by 4.82 °K to 5.52 °K (Figure 6.23). The figure also illustrates evidences of lower rooftop temperature than ceiling temperature particularly at nighttime. This phenomenon testifies substantially the potential of nocturnal cooling of the roof.

The representative day temperature (Figure 6.25) expresses almost identical thermal profile between ceiling and rooftop temperature. Both the magnitude and fluctuation of rooftop temperature are reduced by the introduction of operable roof insulation as compared to uninsulated roof indicating the effectiveness and justification of using operable roof insulation.

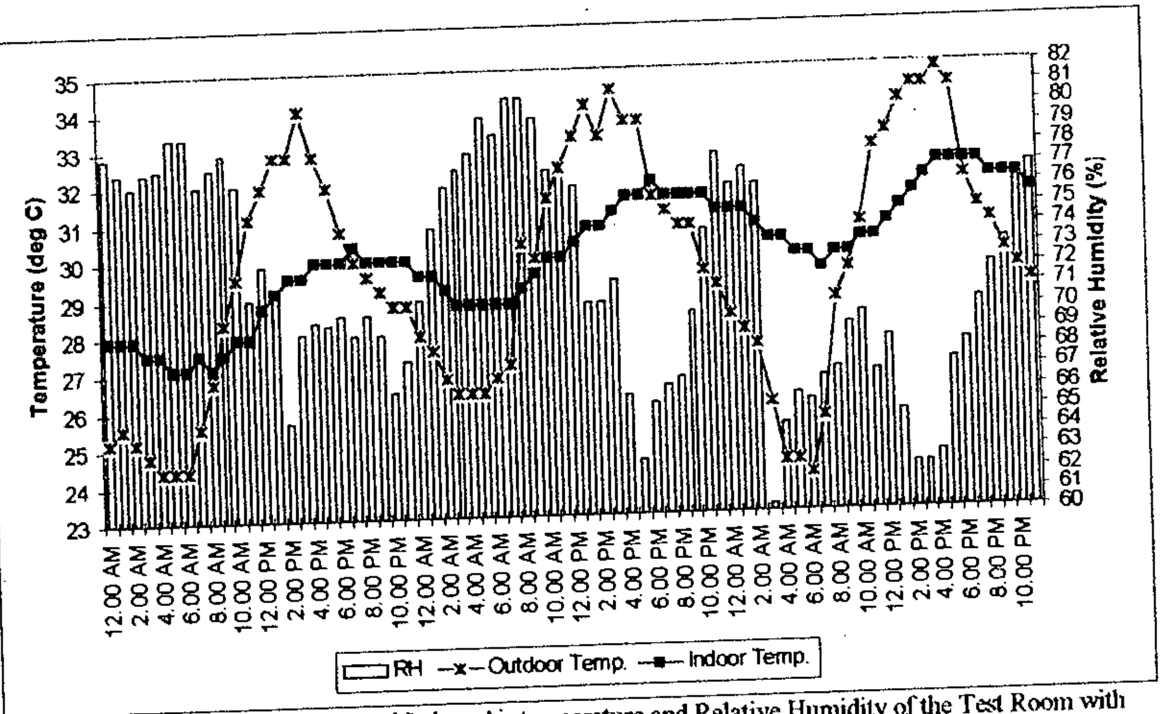

Figure 6.22 Profile of Outdoor and Indoor Air temperature and Relative Humidity of the Test Room with Operable Roof Insulation at 450 mm above the roof (23-25 April, 2002)

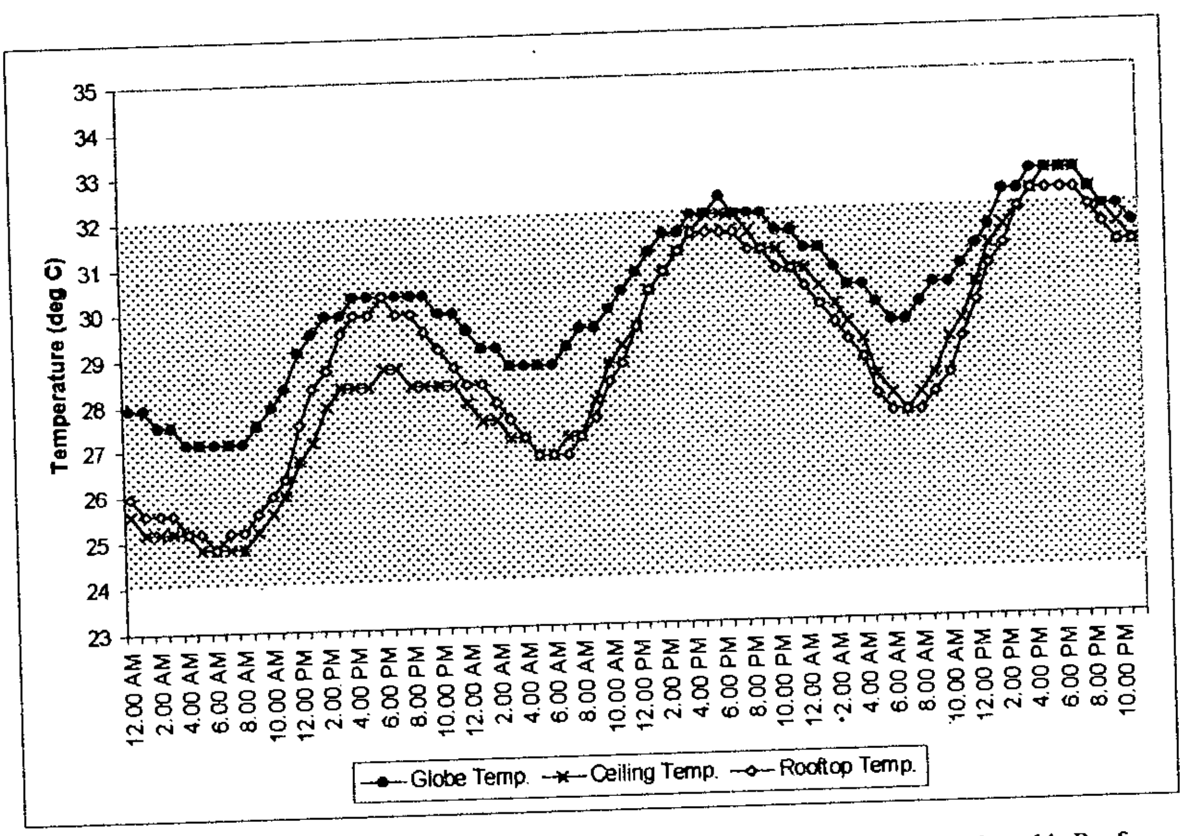

Figure 6.23 Profile of Globe, Ceiling and Rooftop temperature of the Test Room with Operable Roof Insulation at 450 mm above the roof (23-25 April, 2002)

within comfort temperature

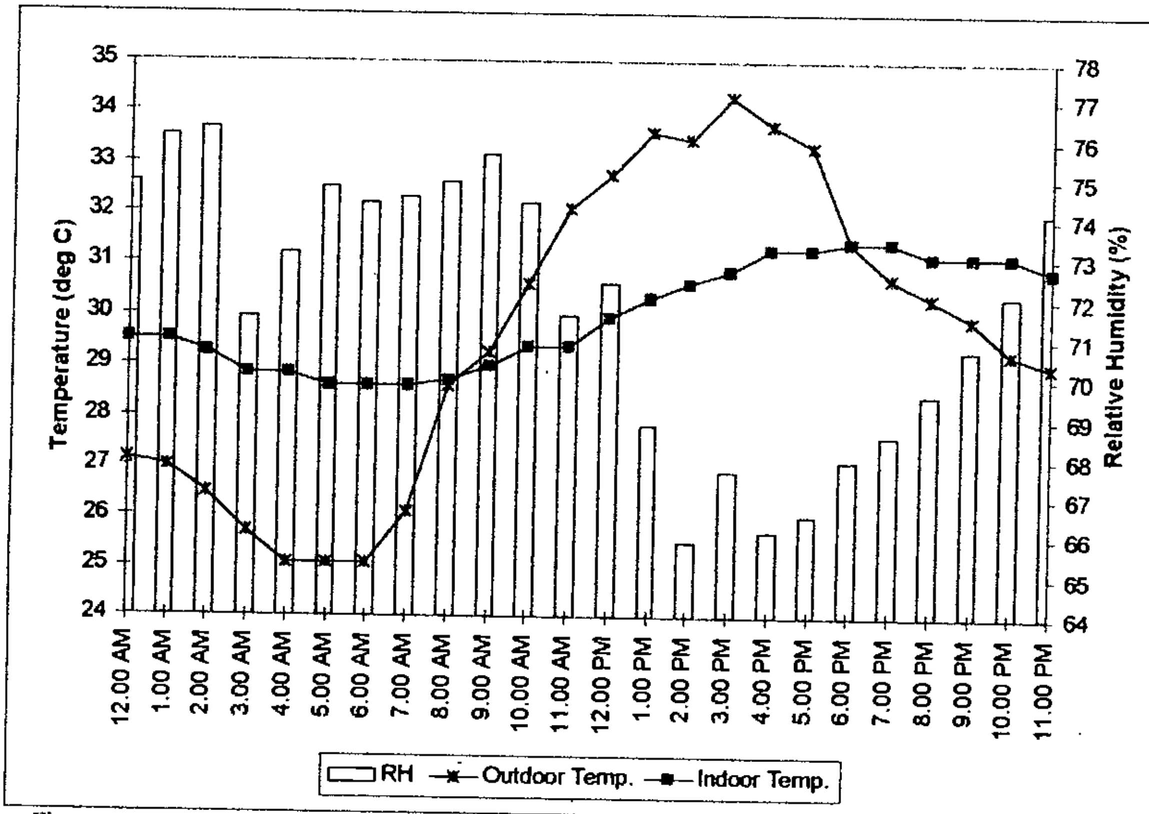

Figure 6.24 Profile of Average Outdoor and Indoor Temperature and Relative Humidity of the Test Room with operable roof insulation at 450mm above the roof. (23-25 April, 2002)

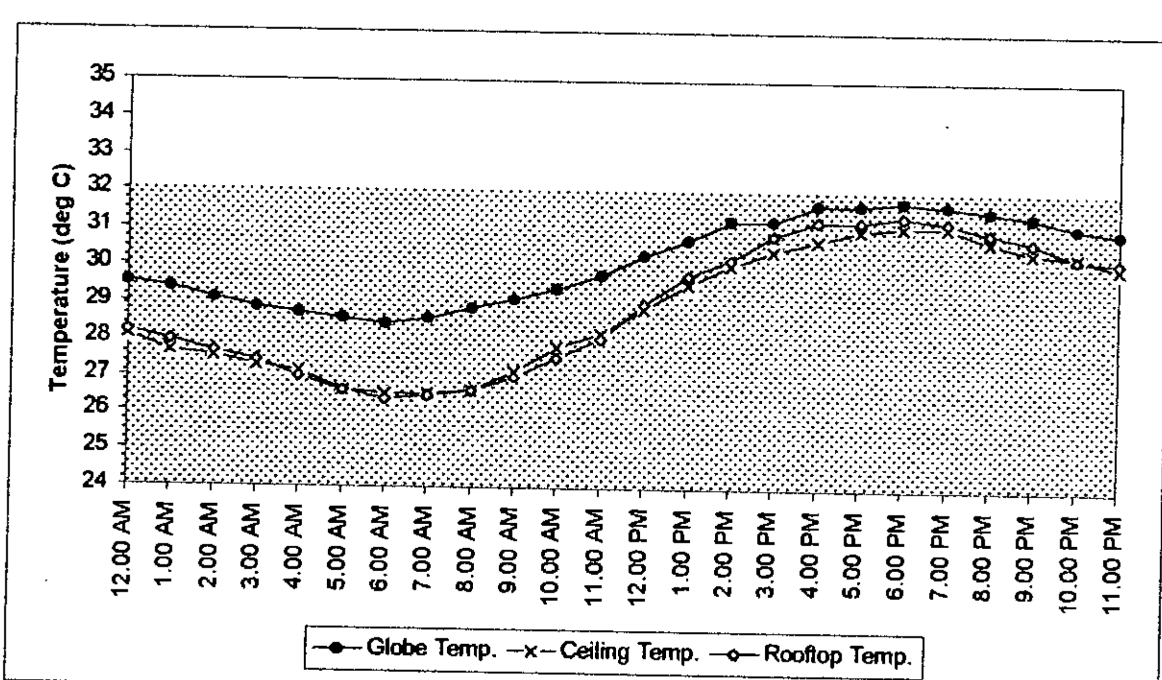

Figure 6.25 Profile of Average Globe, Ceiling and Rooftop Temperature of the Test Room with operable roof insulation at 450mm above the roof (23-25 April, 2002)

within comfort temperature

ii) At 300 mm above the Roof

Simulation study was performed in May with insulation, which is hot-dry season and distinguished by high temperature and radiation. Cloud cover is moderately high (5 octa) and longer sunshine hour is observed (see chapter two and appendix 5 for more climatic details of Dhaka). As this month is important from climatic aspects, followings are the significant environmental findings from field study of the test room with operable roof insulation at 300 mm above the roof:

a) Indoor Air Temperature

The average indoor air temperature was 29.93 °C recorded during the period of field data collection which is well within the comfort range in still air situation. The diurnal difference of maximum and minimum temp. ranges between 2.82 °K to 3.98 °K Time lag varies between 7 to 9 hours (Figure 6.26)

According to average temperature profile for the representative day (Figure 6.28), indoor temperature ranges between 28.31 °C to 31.66 °C creating a difference of 3.35 °K. The temperature fluctuation is minimum, which helps to acclimatize quickly in the test room. While the average outdoors temperature ranges between 26.35 °C to 35.43 °C making a difference of above 9.08°K. According too Figure 6.26 when Outdoor temperature reaches the peak RH goes to the bottom and visc versa. But due to the roof insulation the indoor air temperature measured was always withun summer comfort range with respect to no air condition. It is evident from above facts that roof insulation has impact on indoor temperature at this height.

b) Globe Temperature (GT)

The average GT during the field survey was recorded as 30.09 °C, which is within summer comfort range in still air situation. The Globe maximum temperature was registered as 32.76 °C (just over the comfort range) and the minimum as 27.12 °C, creating a difference of 5.64 °K. The diurnal difference of maximum and minimum GT was recorded between 3.26 to 3.98 °K and the time lag between them varies by 4 to 5 hours (Figure 6.27).

The representative day summary of environmental variables (Figure 6.29) illustrates that GT ranges between 28.44 °C to 31.8 °C (within comfortable range according to Mallick, 1994 and same as 450mm insulation height) Lower temperature regime was observed in the morning hours while the higher regime during noon and evening hours. The average Globe, Ceiling and Rooftop temperature followed a similar pattern during observation period with maximum deviation of 1.44 °K among them. Figure 6.27 also illustrates that from 5 PM to 9 PM Globe temperature reading was below the reading of rooftop temperature. Above circumstances give evidence that even in this height of roof insulation, it has bearing on GT.

c) Ceiling Temperature

According to the logged data the maximum ceiling temperature during the field investigation was recorded as 32.76 °C. The minimum ceiling temperature was recorded as 25.17 °C; thus creating a difference of 7.59 °K. Time lag between day maximum and minimum was registered by 8 to 10 hours. The diurnal maximum and minimum temperature varies between 2.8 ° K to 5.14 °K (Figure 6.27).

The representative day ceiling temperature profile (Figure 6.29) indicates that it almost followed the same track as Rooftop temperature and ranges between 27°C to 31.13 °C (generating moderate temperature fluctuation), which is again within summer comfort zone. It is obvious from all the above facts that roof insulation has bearing on ceiling temperature at this height.

d) Roof Top Temperature

The average rooftop temperature recorded during the field study was 29.27 °C. The maximum temperature was recorded as 33.17 °C while the minimum was 24.79 °C. The diurnal variation between maximum and minimum temp. ranges by 4.02 °K to 5.52 °K (Figure 6.27). The figure also illustrates some evidences of lower rooftop temperature than ceiling temperature particularly at nighttime. This is due to the potential of nocturnal cooling of the roof.

The representative day temperature (Figure 6.29) expresses similar thermal profile between ceiling and rooftop except few hours after evening. Both the magnitude and fluctuation of rooftop temperature are reduced by the introduction of operable roof insulation as compared to uninsulated roof indicating the usefulness and validation of using operable roof insulation. Insulation also increases Thermal Time Constant[4] (TTC), which helps in achieving thermal comfort.

[4] The TTC is the effective product of the thermal resistance and heat capacity of an envelope element. Its unit is time (hours). The TTC is the sum of the products of heat capacity and resistance values of the different layers, when the resistance of each layer is calculated from the external surface. TTC of an element is the main property, in un-air conditioned buildings, which determines the effect of this element on the damping of the indoor temperature swing, relative to the outdoor swing (Givoni,1998).

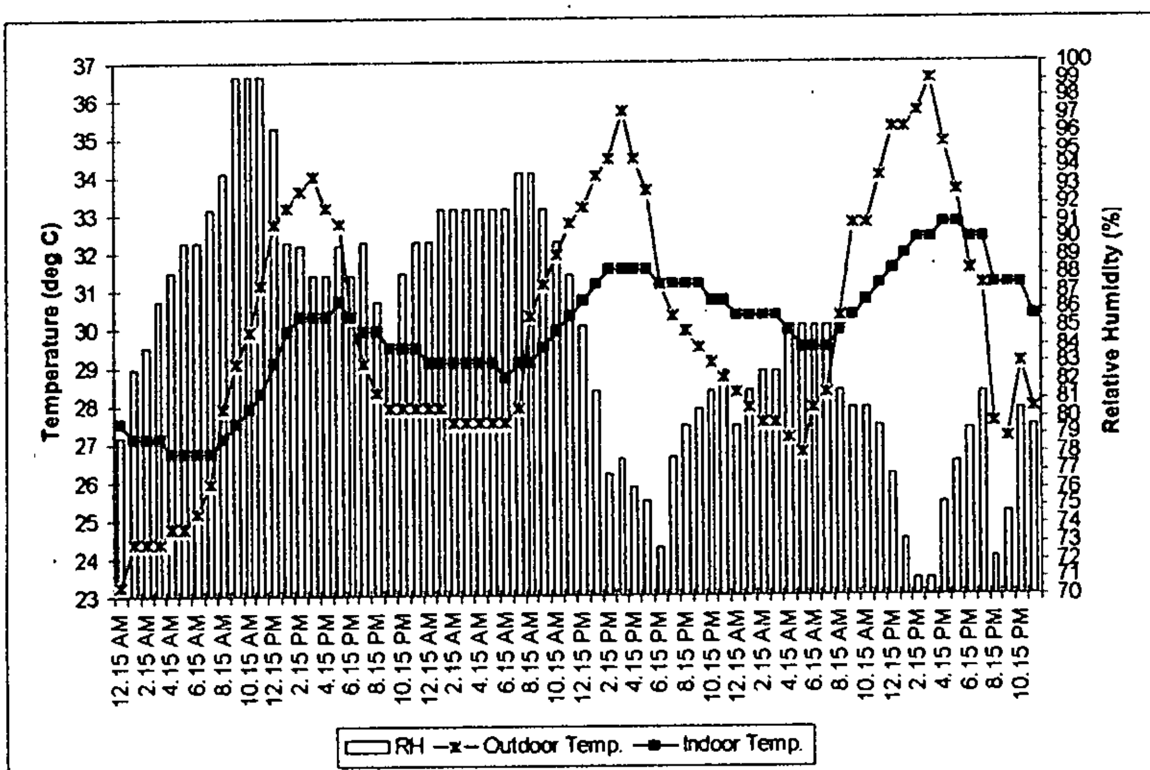

Figure 6.26 Profile of Outdoor and Indoor Air temperature and Relative Humidity of the Test Room with Operable Roof Insulation at 300 mm above the roof (12-14 May, 2002)

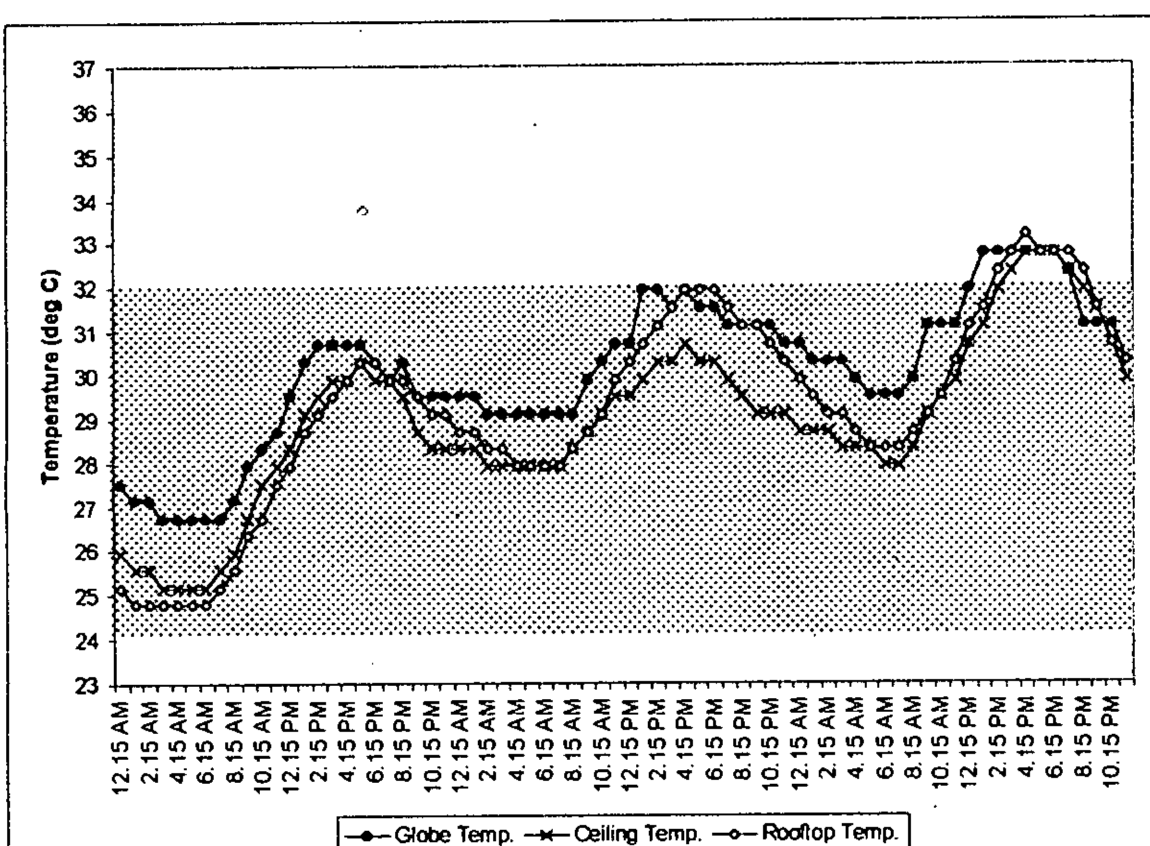

Figure 6.27 Profile of Globe, Ceiling and Rooftop temperature of the Test Room with Operable Roof Insulation at 300 mm above the roof (12-14 May, 2002)

within comfort temperature

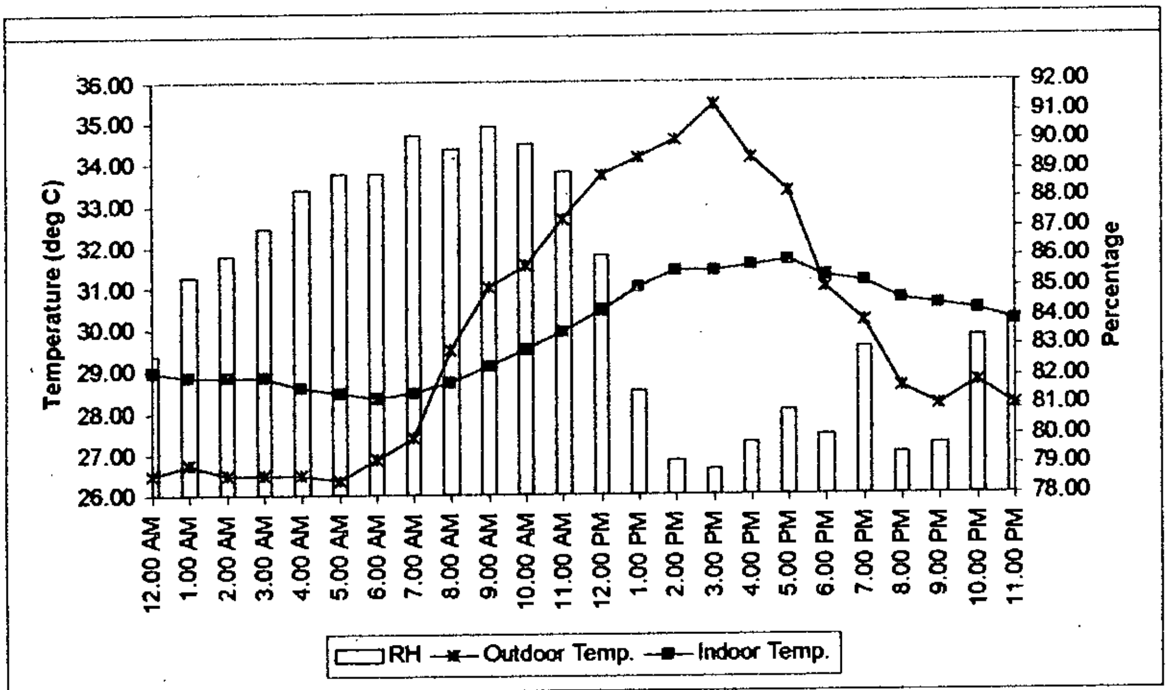

Figure 6.28 Profile of Average Outdoor and Indoor Temperature and Relative Humidity of the Test Room with operable roof insulation at 300mm above the roof (12-14 May, 2002)

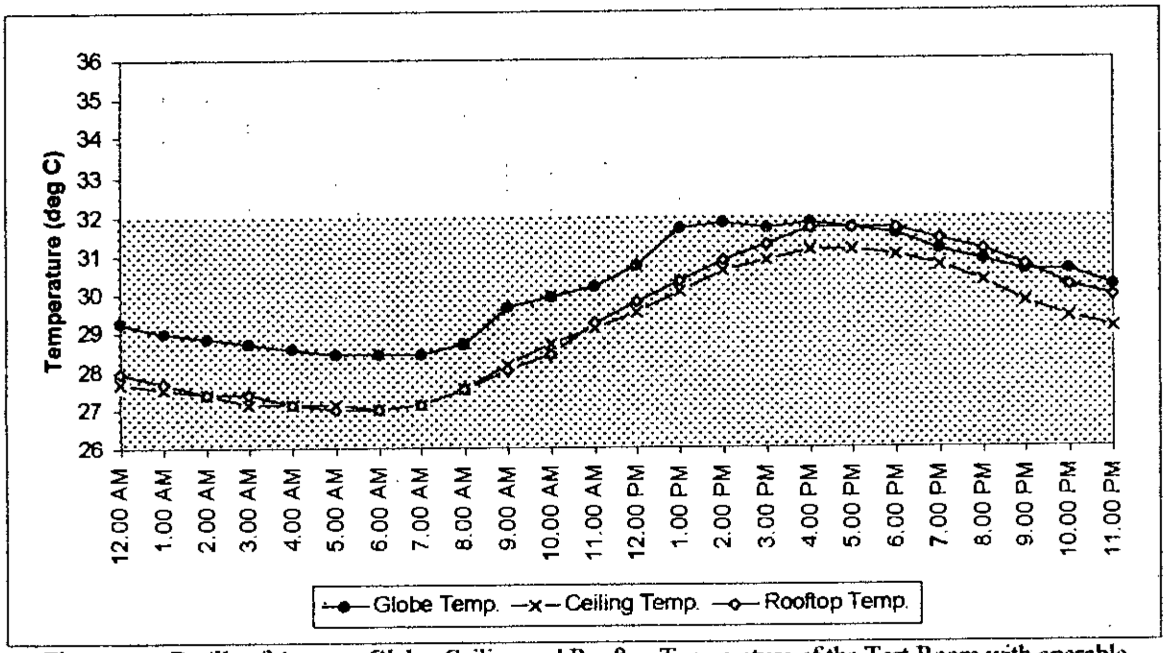

Figure 6.29 Profile of Average Globe, Ceiling and Rooftop Temperature of the Test Room with operable roof insulation at 300mm above the roof (12-14 May, 2002)

within comfort temperature

6.5 COMPARATIVE STUDY

Foregoing sections describe the thermal environment in the test room with respect to uninsulated and insulated (operable) roof. A comparative study is made to judge the thermal performance of operable roof insulation with respect to thermal comfort. The performance evaluation is made on the basis of Temperature Disparity, Temperature Difference, Temperature Attenuation, Comfort Vote and Comfort Zone analysis. Details are discussed below:

a) Temperature Difference(Roof Top Maximum vs. Ceiling Maximum)

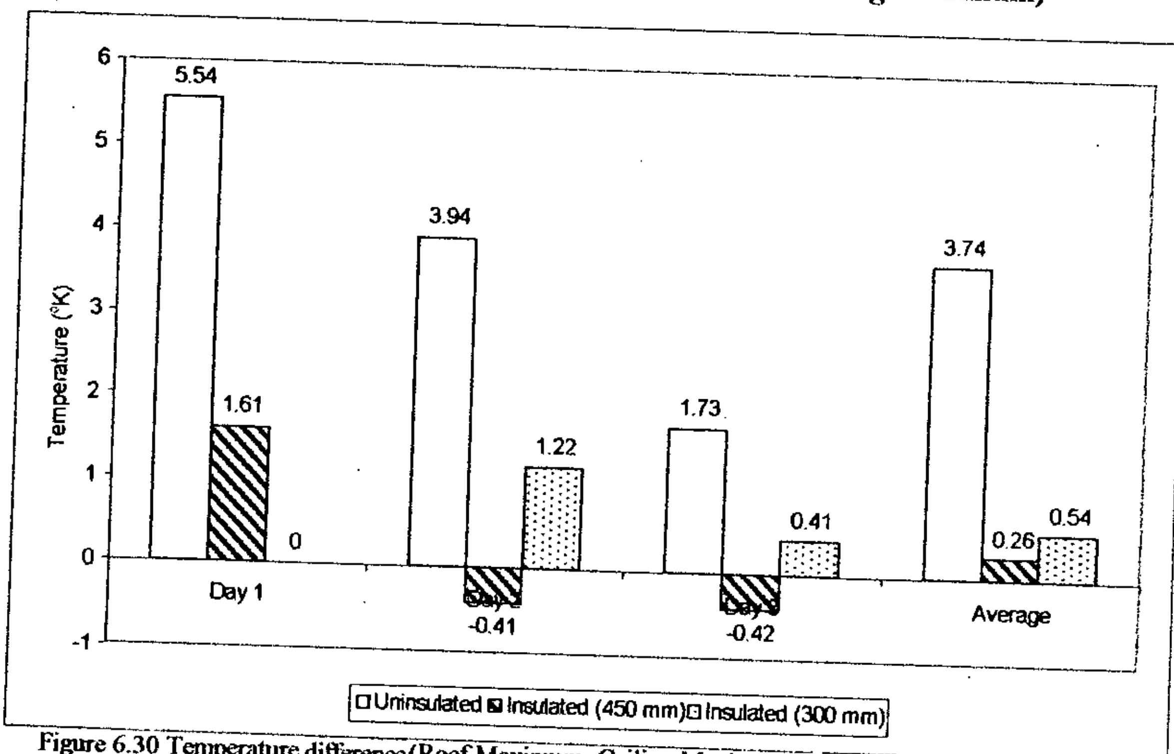

Figure 6.30 Temperature difference(Roof Maximum- Ceiling Maximum) in Test room with Uninsulated and Insulated roof.

According to the field results for uninsulated and insulated roof, considerable amount of temperature disparity between maximum rooftop temperature and maximum ceiling temperature is evident in the test room when the roof is uninsulated. This temperature difference contributes to elevate ambient temperature of the test room and cause discomfort. But when the roof is covered with operable insulation, a different situation is observed. On the first day heat storage is reduced to 1.61 °K while in uninsulated condition it is 5.54 °K during second and third day of data collection roof temperature has gone below the roof temperature when the insulation is placed at 450 mm above the roof; a substantial amount of heat reduction is also evident when insulation is lowered to 300 mm. It testifies the fact that during the daytime, insulation minimizes the heat gain from solar radiation and from the hotter ambient air. The cooled mass of the roof then serves as a heat sink and absorbs through ceiling the heat penetrating into and generated inside the buildings interior during daytime hours. Again when the roof is exposed to night sky it looses heat by long-wave radiation and convection that reduces thermal storage capacity of the roof, therefore ceiling collects heat from the surroundings and may attain higher temperature than roof. Thus, the concrete roofs, which are very common in Dhaka, with applied operable insulation, can provide effective radiant cooling and maintain the indoor temperature well below the outdoor level.

b) Temperature Difference (Globe Maximum vs. Indoor Maximum)

Another way of assessing thermal performance of operable roof insulation was done by measuring temperature difference between Globe Maximum and Indoor Maximum As of all other environmental variables globe temperature is the best indicator of comfort and may be the reason why people feel comfortable at low radiant temperature when air temperature readings are high. (Mallick, 1994)

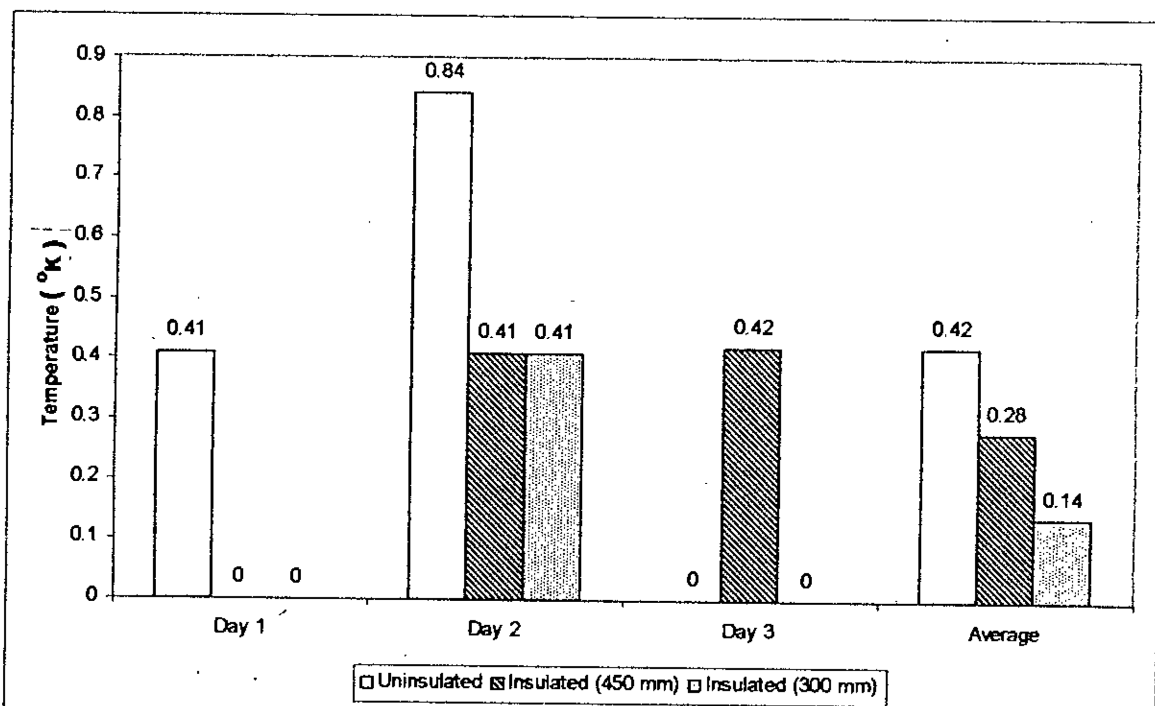

Figure 6.31 Temperature difference between daily Globe Maximum vs. Indoor Maximum in Test room with Uninsulated and Insulated roof.

Temperature difference between daily Globe Maximum and Indoor Maximum clearly indicates that a higher temperature regime exists in the test room when the roof is uninsulated. Not only the magnitude of Globe and Indoor temperature is higher but their difference is also greater (Figure 6.31) in uninsulated situation. On the other hand when the roof of test room is covered by means of operable insulation, a lower temperature prevails as compared to previous one. Insulation reduces the process of heat transfer from roof to the interior, it increases Thermal Time Constant (TTC) (Givoni, 1998) of the material therefore radiant gain becomes slower and accelerates nocturnal cooling process. Therefore in insulated instances we observe almost similar temperature trend between globe and indoor maximum temperature profile and they are within the summer comfort zone in still air condition, while the temperature exceeds the comfort zone in uninsulated situation.

c) Temperature Difference (Outdoor Maximum vs. Indoor Maximum)

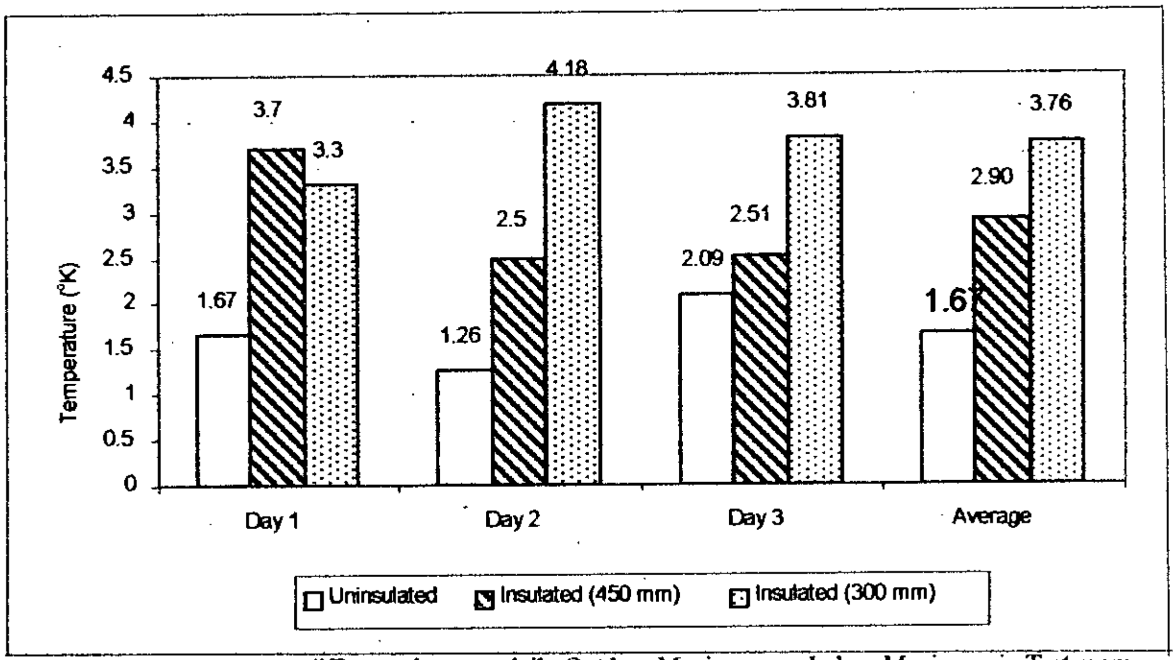

Figure 6.32 Temperature difference between daily Outdoor Maximum vs. Indoor Maximum in Test room with Uninsulated and Insulated roof.

Temperature difference between daily Indoor Maximum and Outdoor Maximum is another indicator by which thermal performance of roof insulation can be judged. Figure 6.32 clearly illustrates that nocturnal cooling potential is pronounced with operable insulation system. Temperature difference between Outdoor and Indoor Max, is negligible, that means almost similar temperature prevails outdoors, as well as indoors with very little cooling potential, whereas with operable insulation system these temperature difference is much distinct (in one instance 4.18 °K), indicating prospect of nocturnal cooling. These phenomena testify the fact that the introduction of operable insulation over the roof not only obstructs the main passage of heat gain (as walls and windows are uninsulated) to the interior but also increases nocturnal cooling potential.

d) Temperature Attenuation

Temperature attenuation between daily Globe Maximum and Minimum in the test room with uninsulated and insulated roof describes certain thermal conditions

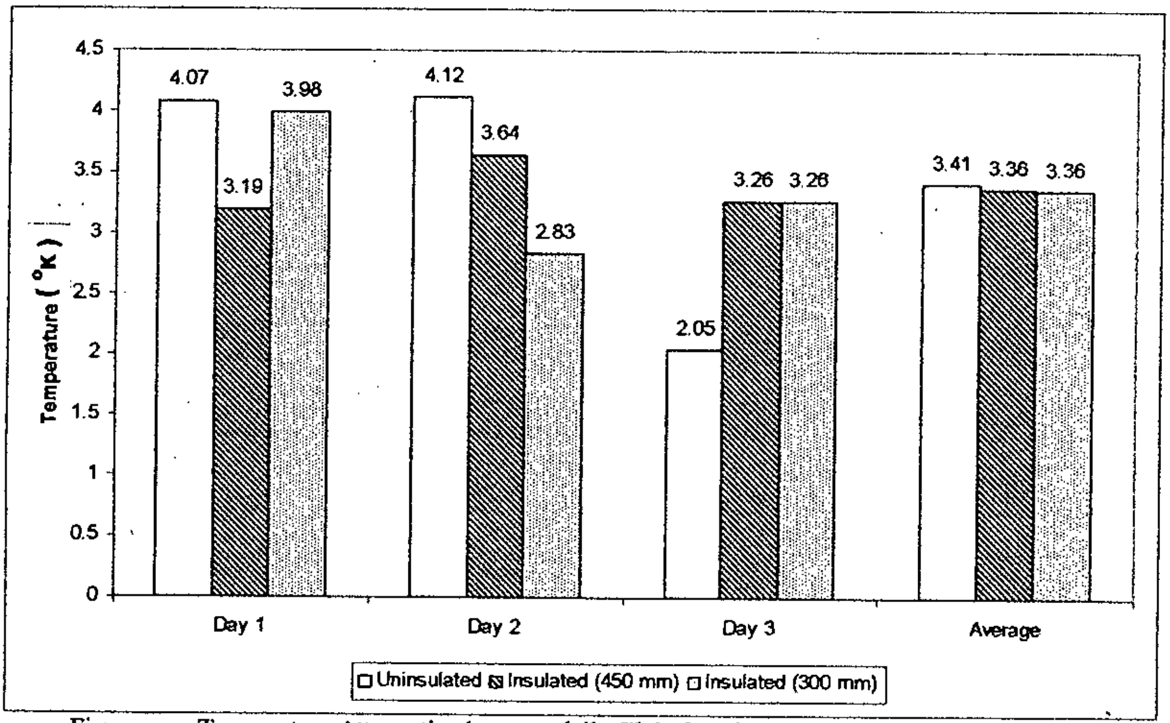

Figure 6.33 Temperature Attenuation between daily Globe Maximum and Minimum in Test room with Uninsulated and Insulated roof.

Figure 6.33 illustrates temperature attenuation for 3 days for the test room with and without insulation on the roof. The average of these are also presented; they are 3.41 °K for uninsulated roof and 3.36 °K and 3.35 °K for insulated roof at 450 and 300 mm height. It is evident that magnitude and fluctuation Globe temperature is higher in uninsulated situation, while it is more stable in insulated roof situation. It is established fact that people's thermal tolerance is increased in more stable thermal condition, therefore later condition if desirable for thermal comfort.

e) Comfort Vote Analysis

Similar to simulation study Comfort Vote Analysis is based on seven-category thermal sensation scale after Bedford and ASHRAE (Mallick, 1994) in the field test. It relates to the sensation of comfort as in the Bedford scale (Bedford, 1936) and borrows from the ASHRAE scale (ASHRAE, 1966) for description of outer categories. Comfort Vote is calculated by the equation $CV = T_g \times .29 - 8$ (Mallick, 1994). The middle three categories (-1,0, +1) accommodate the comfort range.

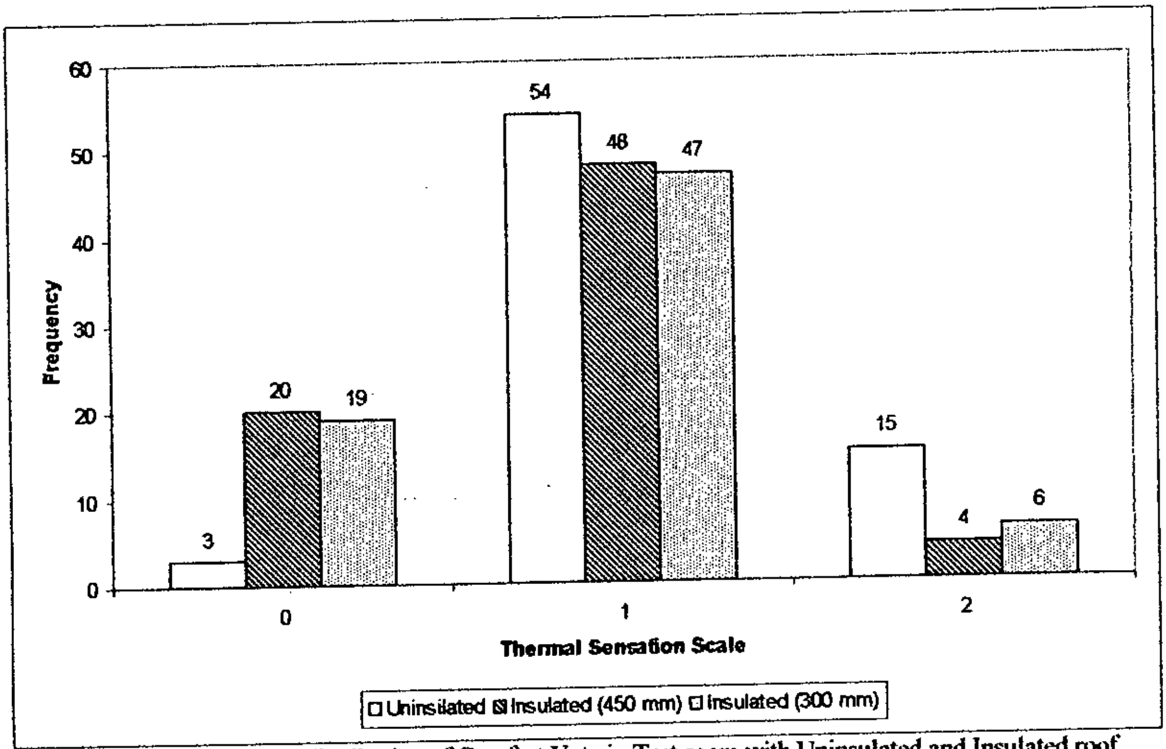

Figure 6.34 Frequency distribution of Comfort Vote in Test room with Uninsulated and Insulated roof.

Comfort vote for uninsulated roof is 3 in comfortable, 54 in comfortably warm category and 15 in warm category. Insulated roof (450mm) receives 20 votes in comfortable, 48 votes in comfortably warm and only 4 votes in warm category, while at 300 mm 19 votes in comfortable, 47 votes in comfortably warm and 6 votes in warm category (Figure 6.34). Only 4% votes are given in comfortable category with uninsulated roof, while it is over 26% with operable insulation. So it is evident that roof with insulation gets majority of votes in comfortable category, which explains its better performance.

f) Comfort Zone Analysis

Comfort zone (further details in chapter three) is outlined on the basis of indoor air temperature, relative humidity and air flow, particularly devised for summer comfort. In still air situation, the boundary conditions for air temperature are between 24-32 °C and upper limit is increased to slightly over 34 °C with .3m/s air speed and nearly 36 °C with .45 m/s air speed.

Figure 6.35 is a scatter diagram showing the relationship between Relative Humidity and Indoor Temperature of the test room with uninsulated roof. After superimposing summer comfort zone on the figure certain thermal information can be traced out.

points are outside the comfort zone (still air situation) and majority of points are concentrated between 70%-85% RH and 30-34 °C. Some of the points are found towards higher relative humidity zone and below 30 °C temperatures. However with the increase of air flow comfortable condition can be achieved.

The diagram for Comfort zone analysis for the test room with operable roof insulation at 450 mm (Figure 6.36) illustrates that, instead of concentrated points they scatter within the comfort zone.

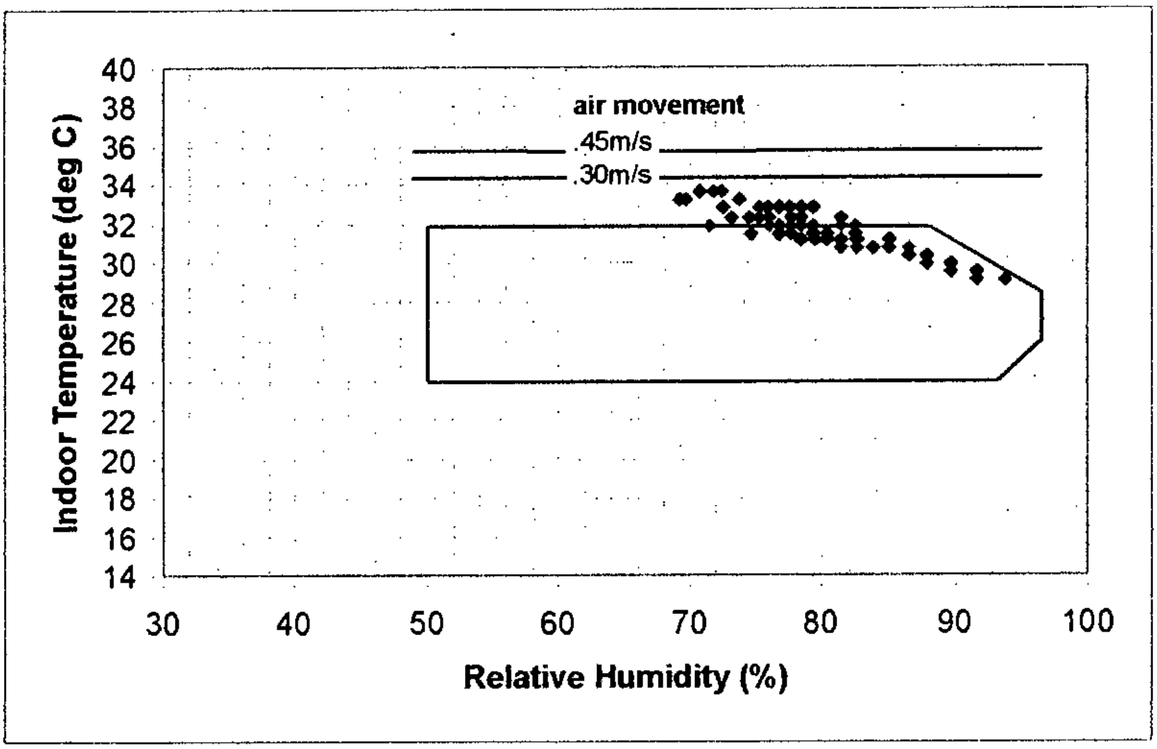

Figure 6.35 Plotting of Indoor Temperature and RH of Test Room with Uninsulated Roof on Summer Comfort Chart

A concentration can be traced between 65-70% relative humidity and 30-32 °C. Very few points are located just outskirt of the higher level of comfort zone. A much better environmental condition exists here as compared to uninsulated condition.

When the height of the roof insulation is reduced to 300 mm then points scatter towards higher regime of relative humidity. Major concentrations occur between 78-82% relative humidity and 30-32 °C. Some points are outside the upper limit of the comfort zone. Very few points are located near 100% relative humidity. This is a condition slightly inferior as compared to insulated situation (Figure 6.37).

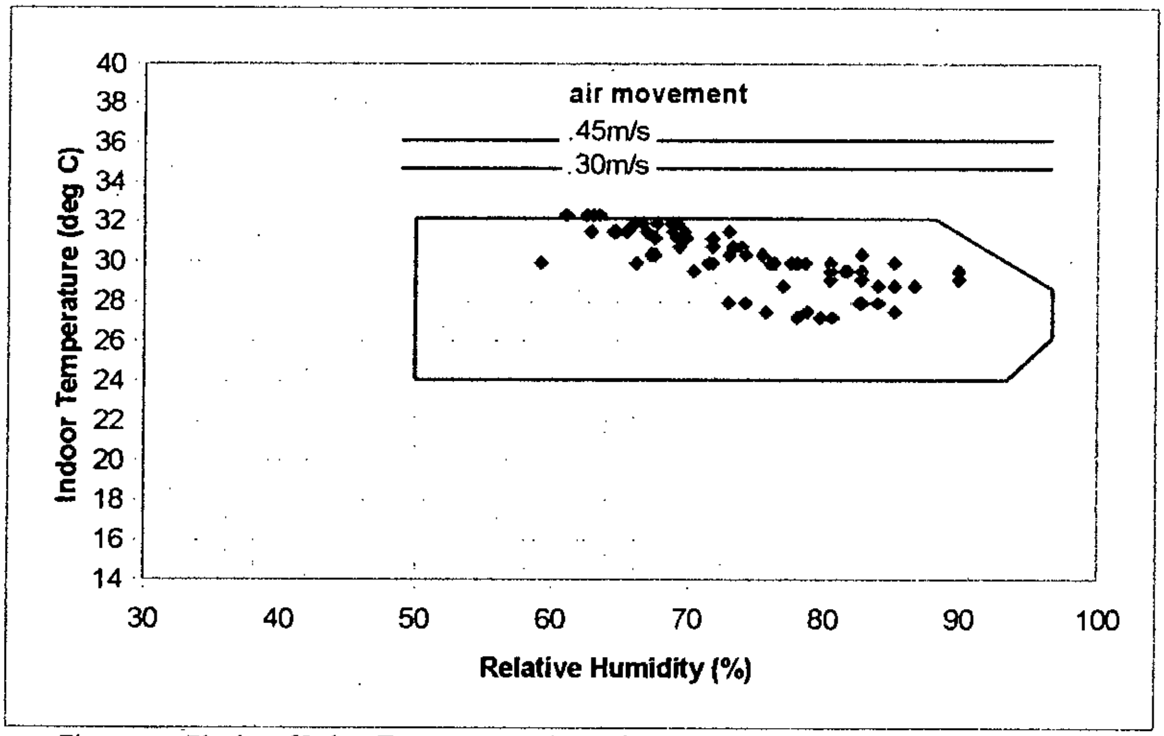

Figure 6.36 Plotting of Indoor Temperature and RH of Test Room with Insulated Roof (450 mm) on Summer Comfort Chart

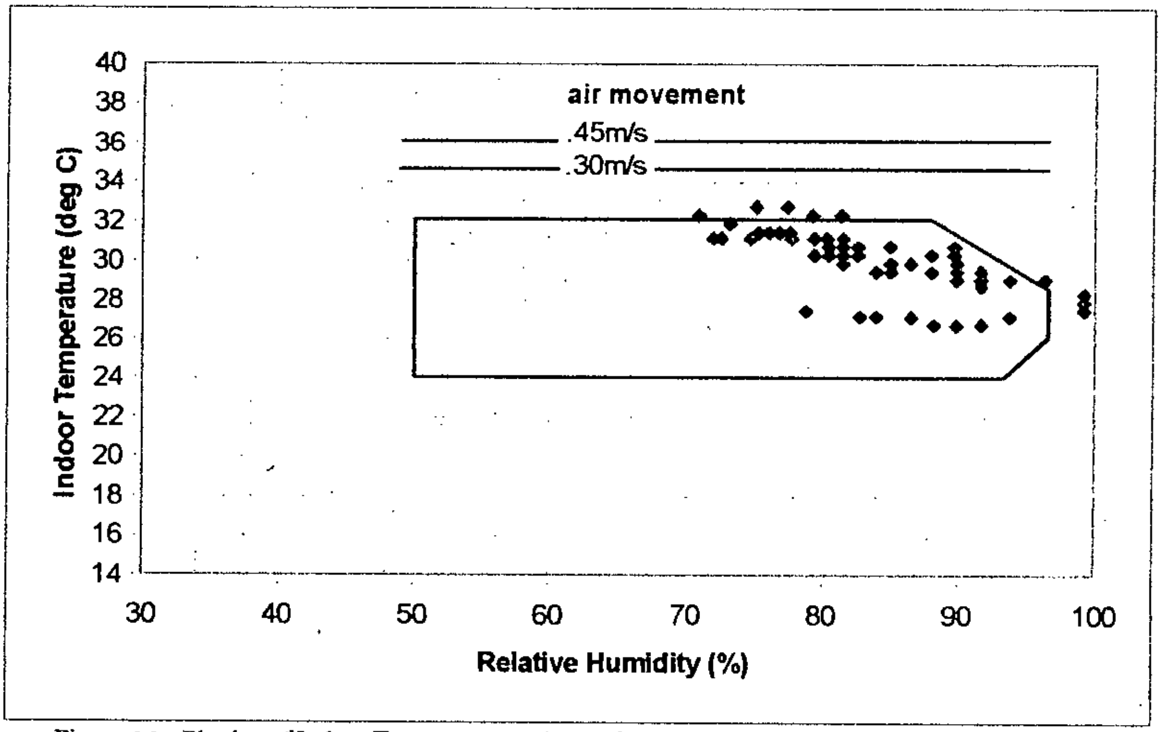

Figure 6.37 Plotting of Indoor Temperature and RH of Test Room with Insulated Roof (300 mm) on Summer Comfort Chart

6.6 CONCLUSION

The above-mentioned findings establish that test room with operable insulation attains more comfortable situation. Obviously the indoor environment is better in comparison to uninsulated situation. Insulation not only cuts down the effect of sol-air-temperature on the roof, which is the main source of heat gain in Dhaka and keep Globe temperature within comfortable range but it also facilitates nocturnal cooling potential. Situations like Dhaka where majority of the time in monsoon and post monsoon period sky is overcast with cloud; even in this circumstances principle of operable insulation works. So this system of roof insulation can be applied to single storied buildings and top floor of multistoried buildings as it leads to better thermal environment performance.

6.7 REFERENCES

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CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

7.1 INTRODUCTION

In order to arrive at some reasonable conclusion and recommendation regarding the roll of nocturnal cooling potential and thermal performance of operable roof insulation in Dhaka, it was necessary to consider how environmental conditions of the test room is influenced by the application of operable roof insulation and compared with the base case (test room without roof insulation). The following conclusions and recommendations were derived from the pervious sections of this thesis work where further simulation study was conducted to see the effect of fixed insulation at different heights that were not covered by field investigation.

7.2 SIGNIFICANT FINDINGS

Significant findings drawn from the performance of operable roof insulation is based on some performance factors. These factors are derived from certain environmental criteria of the test room for the representative day during field investigation:

7.2.1 Temperature Difference (Rooftop vs. Ceiling)

The exterior of the building envelope is alternately heated during day and cooled at night. Part of the heat absorbed during the day warms the mass of the building and only remainder passes to the interior. The ratio between the heat absorbed and that stored in the materials depends mainly on the heat capacity of the envelope. During the summer and in warm regions, the external surface (particularly roof) temperatures are above the internal level (e.g. Ceiling) during day and below it at night. Here, in addition to its quantitative dumping effect on heat exchange, the temperature difference between external and internal surface may also have a qualitative influence on the direction of flow. Therefore the roof slab performance was evaluated by temperature disparity between rooftop and ceiling temperature. One of the intensions of providing operable roof insulation was to reduce storage of heat in the roof slab so that there was less possibility of heat emission to interior. According to performance summary (Table 7.1), mean maximum Rooftop and Ceiling temperature of the test room with uninsulated roof are 42.27 °C and 38.53 °C respectively. Difference between these two is 3.74 °K.

On the other hand temperature difference of the test room with operable roof insulation at 450mm and 300mm above the roof is .26 °K and .57 °K respectively. The magnitude of mean maximum Rooftop temperature and Ceiling temperature are 31.39 °C and 31.13 °C for 450mm height while these temperatures are 31.83 °C and 31.26 °C for 300mm height of operable roof insulation.

It is evident from the above-mentioned fact that not only the magnitudes of mean maximum Rooftop temperature and ceiling temperature is high of the test room without roof insulation but also substantial amount of heat is stored within the roof slab. This may be a vital reason for elevating the indoor air temperature and create discomfort. On the contrary with the use of operable roof insulation, magnitude of mean maximum Rooftop and ceiling temperature are considerably low and within the range of summer comfort zone (as described in previous chapters) and temperature difference between these two factors is negligible (below .5 °K). So Rooftop and ceiling temperature maintains almost similar temperature profile, therefore amount of heat transfer from exterior (roof) to the interior of the test room is less, indicating a good performance of operable roof insulation in terms of comfort and nocturnal cooling potentials.

In simulation study mean maximum rooftop temperature is found as 51.47 °C and mean maximum ceiling temperature is 42.77 °C. When insulation is considered at 5oo mm height from the roof, above-mentioned temperatures generated by the simulation is 52.50 °C and 31.97 °C. Again when the insulation is considered at 200 mm height, mean maximum rooftop and ceiling temperatures are generated as 71.93 °C and 37.27 °C. Therefore temperature difference is 8.7 °K, 20.53 °K and 34.66 °K respectively. These generated data illustrates that magnitude of mean maximum rooftop temperature are very close for uninsulated roof and roof with insulation at 500 mm height. Mean maximum ceiling temperature is lowest and within comfort temperature in still air condition with insulation (500 mm height). So test room condition with insulation at 500 mm height shows better performance among these three conditions.

7.2.2 Radiant Temperature

For a person in an enclosed environment, where the temperature difference between the body and the surrounding surfaces is small, the heat exchange by radiation depends on the mean radiant temperature. When air and mean radiant temperatures are not the same, the Globe temperature is a reasonable measure of the resulting environmental temperature.

Thermal performance of operable roof insulation has also been statistically analyzed by correlation[1] between ceiling temperature and globe temperature. Correlation between these two temperatures for uninsulated roof and roof with operable insulation at 450mm and 300mm height are .95, .98 and .95 respectively. According to statistical analysis 1 is the highest correlation between two factors, so operable roof insulation at 450 mm above the roof represents highest correlation between Ceiling and Globe temperature among other mentioned situations. Here Globe temperature affected by the ceiling temperature. Therefore if ceiling temperature can be reduced, Globe temperature is also reduced, which obviously creates a desirable thermal environment in the test room.

7.2.3 Air Temperature

Heat discomfort inside buildings is correlated mainly with environmental temperature and the airspeed over the body. The environmental temperature expresses the combined effect of the air temperature and mean radiant temperature of the enclosure.

Thermal performance of operable roof insulation is also evaluated by analyzing the magnitude and temperature difference between Globe mean maximum and Indoor mean maximum Air temperature. The performance summary table (Table 7.1) indicates that the magnitude of both Globe and Indoor mean maximum Air temperature in the test room without roof insulation is above comfort level in still air situation.

In other cases (with operable roof insulation at different height from the roof) magnitude of the temperatures are within the comfort range. Although temperature difference between above factors is lower in the case of operable roof insulation at 300mm above the roof in comparison with insulation at 450 mm, but in later circumstances mean maximum indoor temperature is lower hence desirable and illustrates better performance.

Mean maximum globe temperature data generated by simulation study for uninsulated roof and roof with insulation at 500mm and 200mm height are 39.60 °C, 32.83 °C and 36.50 °C respectively. While the mean maximum indoor temperature are 34.70 °C, 29.53 °C and 35.37 °C. The temperature differences are 4.9 °K, 3.3 °K and 1.13 °K. It is evident

[1] This analysis tool and its formulas measure the relationship between two data sets that are scaled to be independent of the unit of measurement. Correlation tool can be used to determine whether two ranges of data move together — that is, whether large values of one set are associated with large values of the other (positive correlation), whether small values of one set are associated with large values of the other (negative correlation), or whether values in both sets are unrelated (correlation near zero)

that magnitude of both the temperatures are above the local comfort level for uninsulated and insulated (200mm) roof but within comfort range when insulation is considered at 500 mm height above the roof.

7.2.4 Temperature Attenuation

In earlier chapters it was mentioned that Globe temperature is the resultant of radiant temperature emitted from all surfaces of a room, therefore it is a major descriptor of thermal comfort in a room. As thermal performance of operable roof insulation is evaluated on the basis of the extent it can provide thermal comfort, temperature attenuation between Globe mean maximum and minimum has been considered as one of the factors of assessment.

Performance summary of temperature attenuation illustrates that Globe mean maximum temperature in the test room without operable roof insulation is above the summer comfort zone, while with operable insulation for both heights (450mm and 300mm) it is within comfort limit even in still air situation, which is obviously preferable than former instance.

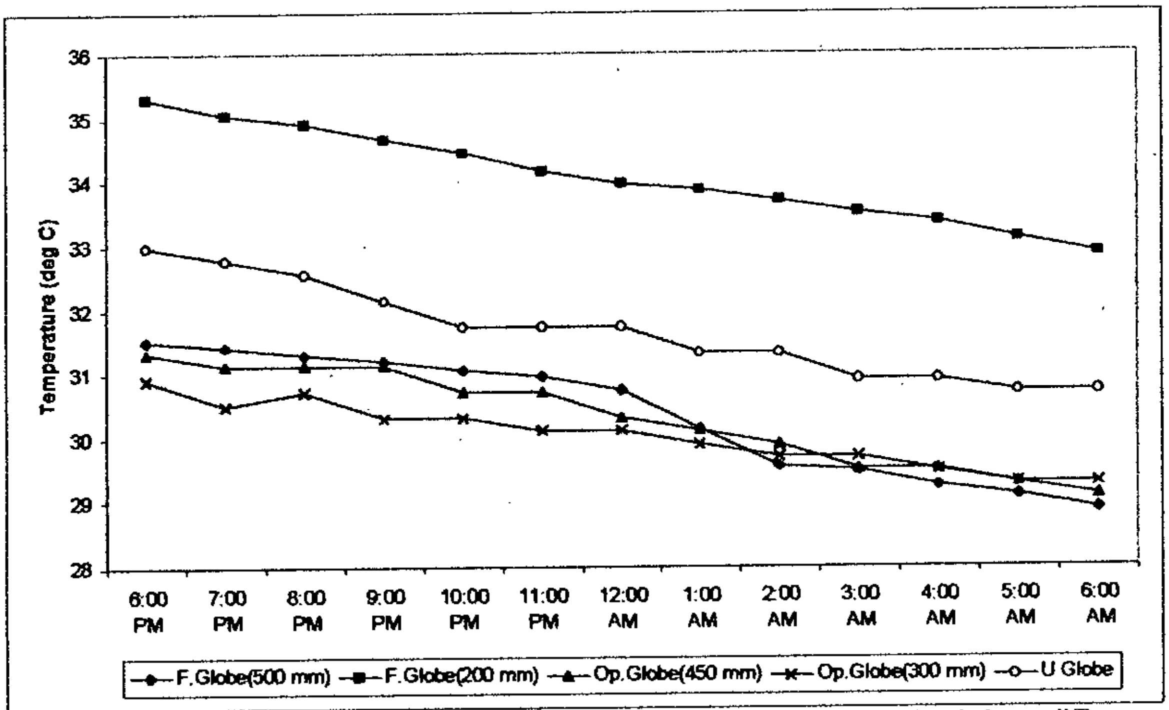
Again the radiant temperature profile generated by simulation illustrates mean maximum and minimum globe temperature in the test room without and with insulation condition. The generated mean maximum globe temperatures are 39.6 °C, 32.83 °C and 36.5 °C while mean minimum are 33.2 °C, 28.87 °C and 32.2 °C respectively. The temperature differences are 6.4 °K, 3.96 °K and 4.3 °K. Test room condition with insulation at 500mm height illustrates best performance as magnitude of temperature is within comfortable range and temperature fluctuation in minimum, which is more thermally agreeable than other test room situation.

7.2.5 Comfort Vote

According to Table 7.1, comfort vote analysis for representative day of the teat room illustrates that test room with operable insulation at 450 mm height gets the maximum number of votes (27.78%) among all other test room conditions in comfortable category while uninsulated roof gets highest vote (20.83%) in warm category.

So it is evident that as roof with insulation gets majority of votes in comfortable category, which explains its better performance.

7.2.6 Nocturnal Cooling



7.1 Average Globe temperature profile in the test room with fixed and operable roof insulation at different height from the roof.

Above illustration describes the average Globe Temperature (GT) in the test room during night (6.00 PM-6.00 AM) with fixed and operable insulation. Globe temperature in relation to fixed roof insulation is designated as 'F.Globe', while Globe temperature in relation to operable roof insulation as 'Op Globe' (with height of the insulation from roof in brackets). 'U Globe' stands for Globe temperature in the test room with uninsulated roof.

According to Figure 7.1 Globe Temperature in the test room with regard to fixed insulations and without insulation demonstrates higher temperature profile as compared to operable insulation. For example 'F Globe (200mm)', temperature ranges between 33-35 °C and 'F Globe (500mm)', temperature ranges between 29-31.5 °C. 'U Globe' temperature during night ranges between 32-33 °C. While both 'Op Globe' temperatures (450mm and 300mm) varies between 29-31.2 °C. An average temperature difference of 3.5- 4 °K is observed between 'F Globe (200mm)' and both 'Op Globe' temperatures and 2-3 °K between 'U Globe' and 'Op Globe' temperatures.

It is evident that Globe temperature in the test room with operable roof insulation at night is within the range of summer comfort zone at still air situation. Furthermore temperature decreases from 6 P.M. to 6 A.M. These phenomena testify the effectiveness of nocturnal cooling with operable roof insulation over without and fixed roof insulation.

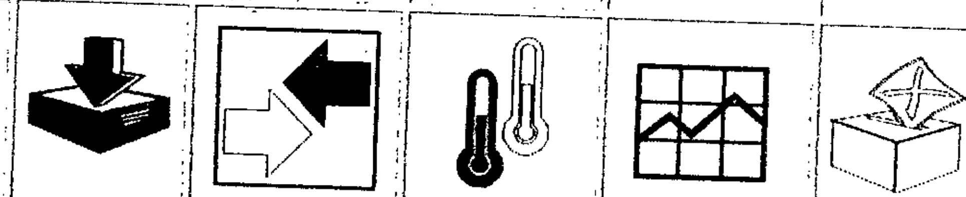
Table 7.1 Performance Summary[1] Table

Temperature Disparity				
	Rooftop Temp (°C) (Mean Maximum)	Ceiling Temp. (°C) (Mean Maximum)	Difference (°K)	Comments
Uninsulated Roof	42.27	38.53	3.74	Undesirable
Insulated Roof (at 450mm height)	31.39	31.13	0.26	Desirable
Insulated Roof (at 300mm height)	31.83	31.26	0.57	Tolerable
Radiant Temperature				
		Ceiling Temp. (°C)	Globe Temp. (°C)	Comments
Uninsulated Roof	Ceiling Temp. Globe Temp.	1 0.95	 1	Better Relation
Insulated Roof (at 450mm height)	Ceiling Temp. Globe Temp.	1 0.98	 1	Best Relation
Insulated Roof (at 300mm height)	Ceiling Temp. Globe Temp.	1 0.95	 1	Better Relation
Air Temperature				
	Globe Temp. (°C) (Mean Maximum)	Indoor Air Temp. °C) (Mean Maximum)	Difference (°K)	Comments
Uninsulated Roof	33.45	33.03	0.42	Undesirable
Insulated Roof (at 450mm height)	31.83	31.52	0.31	Desirable
Insulated Roof (at 300mm height)	31.80	31.66	0.14	Tolerable
Temperature Attenuation				
	Globe Temp. (°C) (Mean Maximum)	Globe Temp. (°C) (Mean Minimum)	Difference (°K)	Comments
Uninsulated Roof	33.45	30.04	3.41	Undesirable
Insulated Roof (at 450mm height)	31.83	28.44	3.39	Tolerable
Insulated Roof (at 300mm height)	31.80	28.44	3.36	Desirable

Comfort Vote					
	Thermal Sensation Scale[2]	Frequency	Individual (%)	Cumulative (%)	Comments
Uninsulated Roof	Comfortable Comfortable Warm Warm	3 54 15	4.17 75 20.83	4.17 79.17 100	Undesirable
Insulated Roof (at 450mm height)	Comfortable Comfortable Warm Warm	20 48 4	27.78 66.67 5.56	27.78 94.45 100	Desirable
Insulated Roof (at 300mm height)	Comfortable Comfortable Warm Warm	19 47 6	26.39 65.28 8.33	26.39 91.67 100	Tolerable

[1] Performance summary is based on values of representative day which is the average hourly environmental data collected during field investigation.
[2] Thermal sensation is based on seven-category scale after the Bedford and ASHRAE scales of thermal sensation.

Test Room Condition	Temp. Difference (Rooftop vs Ceiling)	Radiant Temperature (Ceiling vs Globe)	Air Temperature (Globe vs indoor air)	Temp. Attenuation (Globe max vs Globe min)	Comfort Vote
Uninsulated	☒	☒	☒	☒	☒
Insulated (450mm)	☑	☑	☑	☐	☑
Insulated (300 mm)	☐	☐	☐	☑	☐



Key: ☑ Desirable ☐ Tolerable ☒ Undesirable

Figure 7.2 Performance evaluation of operable roof insulation for the Test room with different insulation condition

7.3 CONCLUSION AND RECOMMENDATIONS

It is evident from all above circumstances that operable roof insulation demonstrates a better performance with respect to base case situation (Test room without operable roof insulation), as environmental conditions are better in terms of comfort in the Test room. Performance evaluation between the operable roof insulation at 450mm and 300mm height above the roof confirms that roof insulation at relatively higher height performs better than lower height (Figure 7.2).

A major purpose of this research work was to testify the feasibility of nocturnal cooling concept in climatic condition like Dhaka (where except few months in winter, most of the period of the year the sky is considerably covered with clouds). However, the investigation confirms that even in this kind of climatic condition, the concept of nocturnal cooling can work to achieve comfortable environmental condition. Moreover the performance can be further improved in relatively clear sky condition in dry months.

The intention of this research work is to provide an introduction or preliminary guideline for thermally responsive architecture on the basis of thermal performance of operable roof insulation. Even though the operable roof insulation at the height of 450mm above the roof proved to be thermally satisfactory, the following recommendations may improve its thermal performance even further:

- A minimum of 450mm height of parapet is desirable, higher height may be recommended.
- Solidly constructed parapet wall up to 450mm above the roof is recommended to prevent air leakage hence convective gain. Perforation on the parapet for aesthetic purpose can be done over the level of 450mm
- More reflective the envelop for insulating material better the thermal performance of the operable roof insulation.
- To prevent sagging of the insulation due to its self-weight, twisted stainless steel cable can be used instead of Galvanized Iron (GI) wire as channel for operability.
- Roofs should be adequately graded and equipped with properly drainage system so that no water logging occurs after rain.
- In winter to trap the heat in the room the process of exposing and covering the roof by insulation should be reversed as compared to summer situation i.e. roof should de exposed to solar radiation during day time and covered by operable insulation during night time.
- For summer condition, to ensure good performance, the operable roof insulation should be opened (retracted) soon after sun set and should be covered before sunrise.
- Application of operable roof insulation may be better in northern region of Bangladesh where summer is relatively drier.

7.4 SUGGESTION FOR FURTHER RESEARCH

In order to continue the pursuit of knowledge in the thermal performance of operable roof insulation, the following areas of research are suggested:

- The thermal performance of operable roof insulation can be investigated at different heights from the roof.
- Different type of insulating materials can be experimented to observe the performance of operable roof insulation.
- Possibility of mechanized operable insulation can be explored with the help of light sensors and motors.
- The cost effectiveness of lime terracing and other fixed insulation process versus operable roof insulation can be done considering maintenance and construction cost and degradation of insulation.
- Performance evaluation can be done with various thickness of roof slab.
- A holistic evaluation of thermal comfort needs to consider the behavior of the people in all types of buildings in both urban and rural areas and in all seasons.
- The use of building materials and methods with regard to their thermal properties need to be investigated for detailed recommendations for their uses.
- Performance of operable roof insulation and its effect in the test room in winter season can be studied.
- Keeping in view of traditional use of roof in the country, further research on social acceptance of roof with operable insulation system can be conducted.

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APPENDICES

A 1 INSTRUMENTATION

A 2 THE SOFTWARE USED FOR THE THESIS

A 3 SIMULATION DATA

A 4 FIELD DATA

A 5 METEOROLOGICAL DATA OF DHAKA

APPENDIX A 1 EQUIPMENT DETAILS

A 1.1 HOBO® H8 Logger for RH/Temp/2x External

Measure:
Temperature
Relative Humidity
2x External

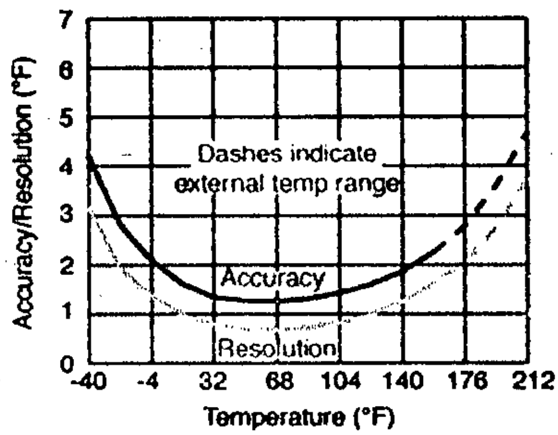
Features and specifications

- Capacity: 7943 measurements total
- User-selectable sampling interval: 0.5 seconds to 9 hours, recording times up to 1 year
- Readout and relaunch with optional HOBO Shuttle
- Internal temperature sensor on 4" wire can extend from case
- Models with external input accept external sensors for temperature, AC current, 4-20 mA and 0-2.5 Volts DC
- Precision components eliminate the need for user calibration
- Drop-proof to 5 feet
- Mounting kit included (hook/loop, magnet, and tape)
- Programmable start time/date
- Memory modes: stop when full, wrap-around when full
- Nonvolatile EEPROM memory retains data even if battery fails
- Blinking LED light confirms operation
- User-replaceable battery lasts 1 year
- Battery level indication at launch
- Operating range: -4°F to +158°F (-20°C to +70°C), 0 to 95% relative humidity, non-condensing, non-fogging (RH sensor range at right)
- Time accuracy: ±1 minute per week at +68°F (+20°C)
- Size/Weight: 2.4 x 1.9 x 0.8" (68 x 48 x 19 mm)/approx. 1 oz.(29 gms)
- Compliance certificate available
- NIST-traceable temperature accuracy certification available

Measurement Specifications

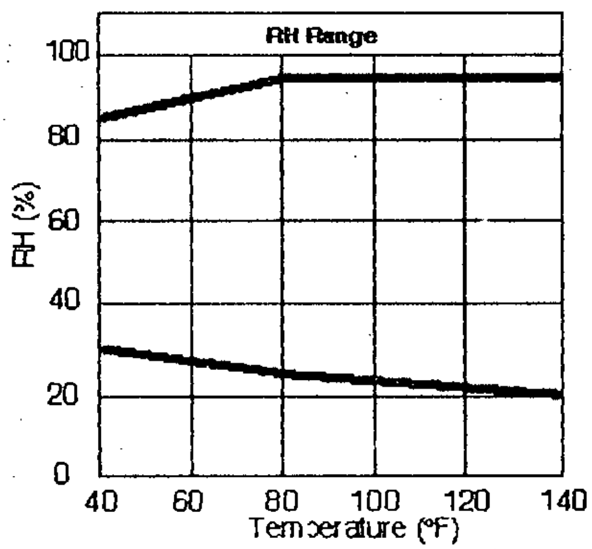
Temperature (internal sensor)

- Range: -4°F to +158°F (-20°C to +70°C)
- Range for internal sensor when used outside of case: -40°F to +248°F (-40°C to +120°C)
- Accuracy: ±1.27°F (±0.7°C) at +70°F, see plot below
- Resolution: 0.7°F (0.4°C) at +70°F
- Response time still in air: 15 min. typical with sensor inside case; 1 min. typical with sensor outside case



Relative humidity (user-replaceable RH sensor)

- Range: 25% to 95% RH at +80°F for intervals of ≥ 10 seconds, non-condensing and non-fogging, see plot below
- Accuracy: ±5%
- Response time 10 min. typical in air
- Sensor operating environment: +41°F to +122°F (+5°C to +50°C) non-condensing and non-fogging



External input accepts the following sensors:

- Wide range of temperature sensors (TMCx-Hx series)
- Split-core CTs for AC current (5 Models)
- 4-20 mA input cable (CABLE-4-20mA)
- 0-2.5 V DC input cable (CABLE-2.5-STEREO)

External 2.5-volt input specifications

- 2.5 mm jack: external input ground, input, switched 2.5 V output; external input ground connection is not the same as PC interface connection ground and should not be connected to any external ground
- Input range: 0 to +2.5 Volts DC
- Accuracy: ±10 mV ±1% of reading
- Resolution: 10 mV (8-bit)
- Out power: +2.5 Volts DC at 2 mA, active only during measurements

Accessories				
Wide-range temperature sensor - 1 ft	TMC1-HA	$23	$21	$20
Wide-range temperature sensor - 6 ft	TMC6-HA	$25	$23	$21
Wide-range temperature sensor - 20 ft	TMC20-HA	$30	$28	$26
Wide-range temperature sensor - 50 ft	TMC50-HA	$35	$33	$30
High-accuracy temperature sensor	TMC6-HB	$40	$37	$34
Stainless steel temperature probe	TMC6-HC	$70	$65	$60
0-20 Amp split-core AC current sensor	CTV-A	$84	$77	$71
0-50 Amp split-core AC current sensor	CTV-B	$84	$77	$71
0-100 Amp split-core AC current sensor	CTV-C	$84	$77	$71
0-200 Amp split-core AC current sensor	CTV-D	$100	$93	$85
0-600 Amp split-core AC current sensor	CTV-E	$100	$93	$85
4-20 mA cable (18 inches)	CABLE-4-20mA	$13	$12	$11
Voltage input cable (6 feet)	CABLE-2.5-STEREO	$6	$5	$4
Adapter for old-style temperature sensors	TMCx-1T-Adapter	$15	$14	$13
Replacement batteries (box of 10)	HRB-TEMP	$15	-	-
Replacement RH sensor	HUM-UPS-500	$16	$15	$14

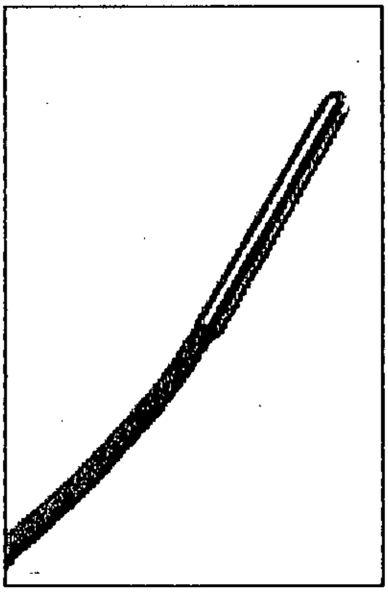
Home | Contact Onset

A 1.2 HOBO H8 External Sensors

All of the cables below can be plugged directly into the external inputs of the HOBO 4-Channel Indoor External, HOBO H8 Outdoor/Industrial 4-Channel, the HOBO H8 RH/Temp/Light/External, the HOBO H8 RH/Temp/2x External, or the HOBO Temp/External data loggers. For other cables, batteries and miscellaneous logger accessories, please see our Replacement Parts & Accessories list.

External Sensors and Input Cables

Wide-range temperature sensors
High-Accuracy temperature sensor (TMC6-HB)
Stainless Steel temperature probe
Split-core AC current sensors
4-20 mA cable
Voltage input cable
Adapter for old style temperature sensors

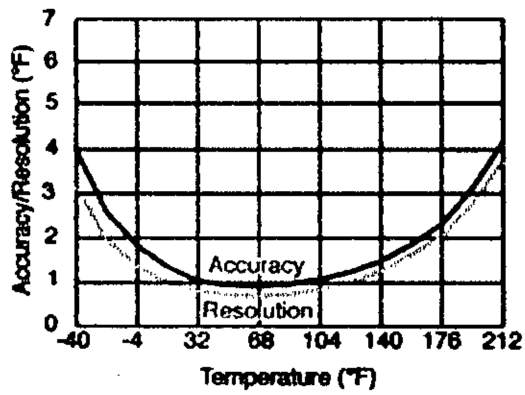


TMC6-HA and TMC6-HB temperature sensors

- Range: -40°F to +212°F (-40°C to +100°C) in air
- Accuracy: ±0.9°F at +70°F (±0.5°C at +20°C), see plot A below (insert probe 0.9" min.)
- Resolution: ±0.7°F at +70°F, (±0.41°C at +20°C), see plot A below
- Response time in still air: 4.5 minute typical
- Response time in stirred water: 1 minute typical
- 0.2" diameter sensor (fits in 1/4" holes)
- Available in 1, 6, 20, and 50 foot cable lengths

Note: TMCx-Ha temperature probes are not intended for prolonged use in water or moist environments, especially those with temperatures greater than 90°F (30°C). The stainless steel tip is waterproof, but water can migrate through the cable jacket over long term immersion.

Plot A
Temperature Accuracy and Resolution



Ordering Information

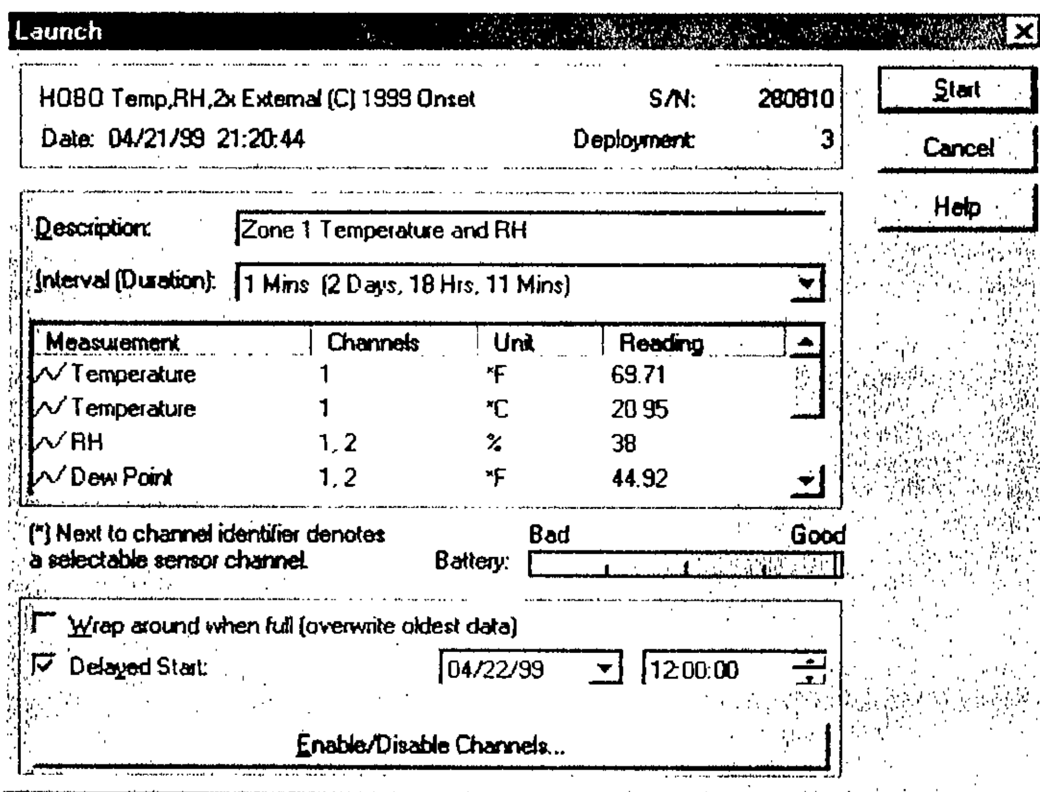
Description	Part No.	Qty 1-9	10-99	100+
Wide range temperature sensor - 1 ft**	TMC1-HA	$23	$21	$20
Wide-range temperature sensor - 6 ft	TMC6-HA	$25	$23	$21
Wide-range temperature sensor - 20 ft**	TMC20-HA	$30	$28	$26
Wide-range temperature sensor - 50 ft**	TMC50-HA	$35	$33	$30
High-accuracy temperature sensor	TMC6-HB	$40	$37	$34
Stainless steel temperature probe**	TMC6-HC	$70	$65	$60
0-20 Amp split-core AC current sensor	CT-A	$84	$77	$71
0-50 Amp split-core AC current sensor	CT-B	$84	$77	$71
0-100 Amp split-core AC current sensor	CT-C	$80	$74	$68
0-200 Amp split-core AC current sensor	CT-D	$80	$74	$68
0-600 Amp split-core AC current sensor	CT-E	$80	$74	$68
4-20 mA cable (18 inches)	CABLE-4-20mA	$13	$12	$11
TMCx-1T-Adapter**	TMCx-1T-Adapter	$15	$14	$13
Voltage input cable (6 feet)	CABLE-2.5-STEREO	$6	$5	$4

APPENDIX A 2 THE SOFTWARES USED FOR THE THESIS

A 2.1 BoxCar Pro 4.0 for Windows

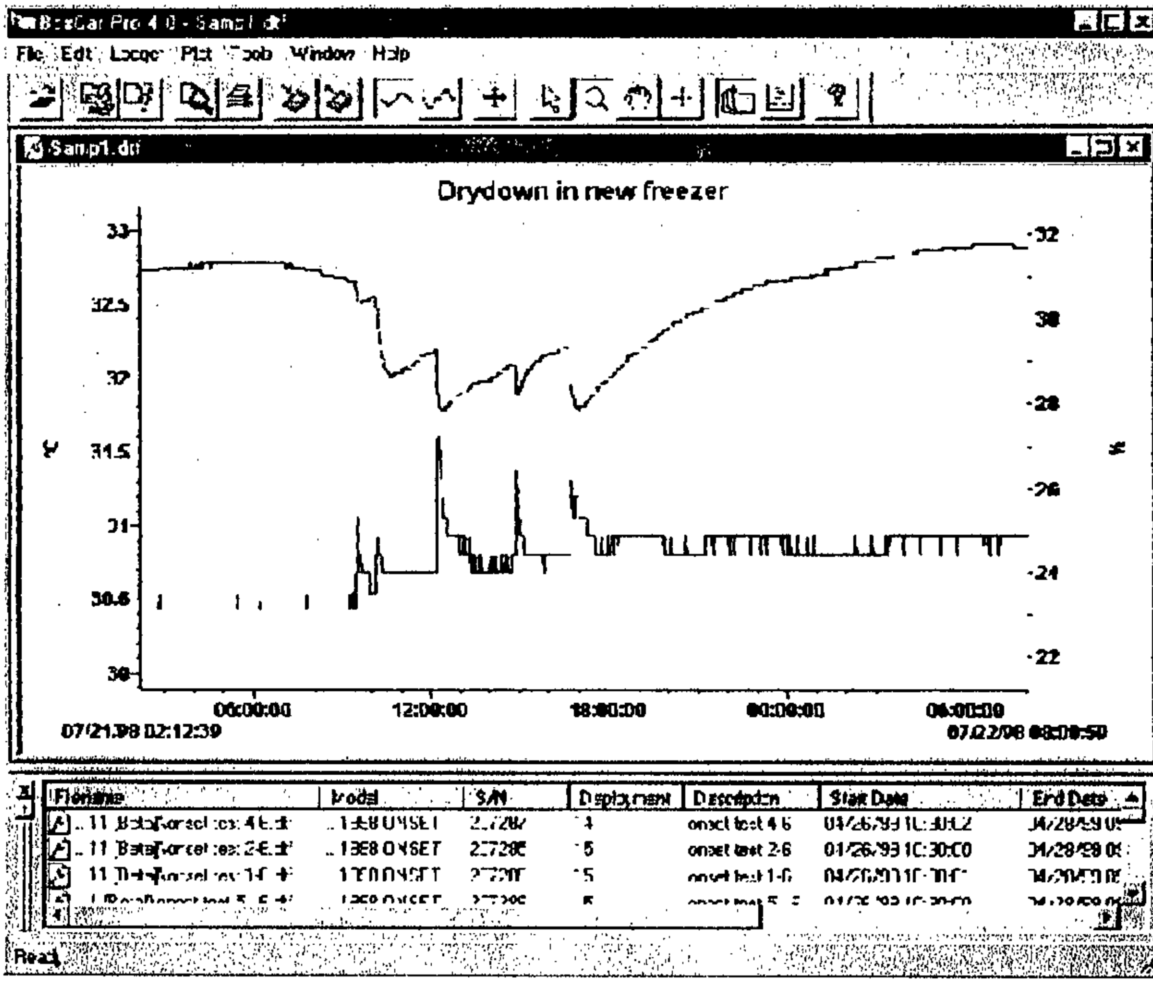
Onset offers two Windows applications for logger and data management. BoxCar Pro 4.0 is a powerful enhanced version of BoxCar 3.7, offering added features for graphing, data analysis, data export and simultaneous management of multiple loggers. BoxCar 3.7 provides basic launch, data readout, plotting and data export capabilities. BoxCar Pro 4.0 and BoxCar 3.7 support all currently available HOBO and StowAway loggers.

Easy Logger Setup



- Select from predefined sampling intervals (0.5 seconds to 9 hours) or program your own custom intervals
- Set start time and memory modes (e.g., stop when full, wrap-around when full)
- Verify logger operation before launching
- Synchronizes logger and data shuttle clocks to computer clock
- Checks battery status (for HOBO H8, HOBO Pro, HOBO H6, HOBO Event and HOBO Shuttle)

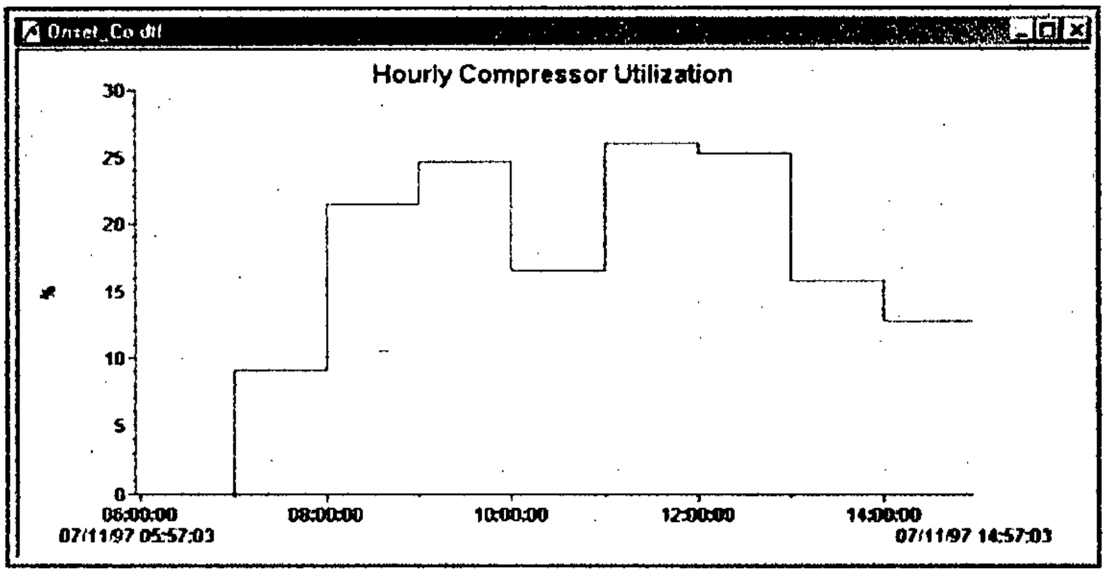
Graphing



Powerful new graphing capabilities allow you to compare multiple parameters on one graph, including data from multiple loggers or successive deployments. Then use the zoom and axis-control tools to focus in on the data of interest.

- Add new data series from stored files or drag-and-drop from one lot onto another
- Multiple value axis on one graph, such as temperature and RH
- View data from successive deployments on one graph to see long-term trends
- Overlay data from different deployments, to compare month-to-month, or before-and-after
- Focus on data of interest with powerful zoom and drag tools
- Set axis ranges
- Use cursor to display specific plot values
- Display series data and details such as launch parameters and series statistics
- Add limit lines to the graph
- Copy and paste graphs into other Windows programs
- Control axis, series and legend properties

Analysis Functions



The following analysis functions can be used to extract key information from logged data. These functions actually create new data series, which can be graphed or exported. These functions filter data over user-specified intervals that can be in seconds, minutes, hours or days.

Min, max and average values per interval

On/off and State logger data:

Run time and off time (closed time and open time) in seconds
Percent on and percent off (percent closed and percent open)
Number of ons and offs (number of opens and closes)

Event logger data:

Rainfall per time interval
Number of events

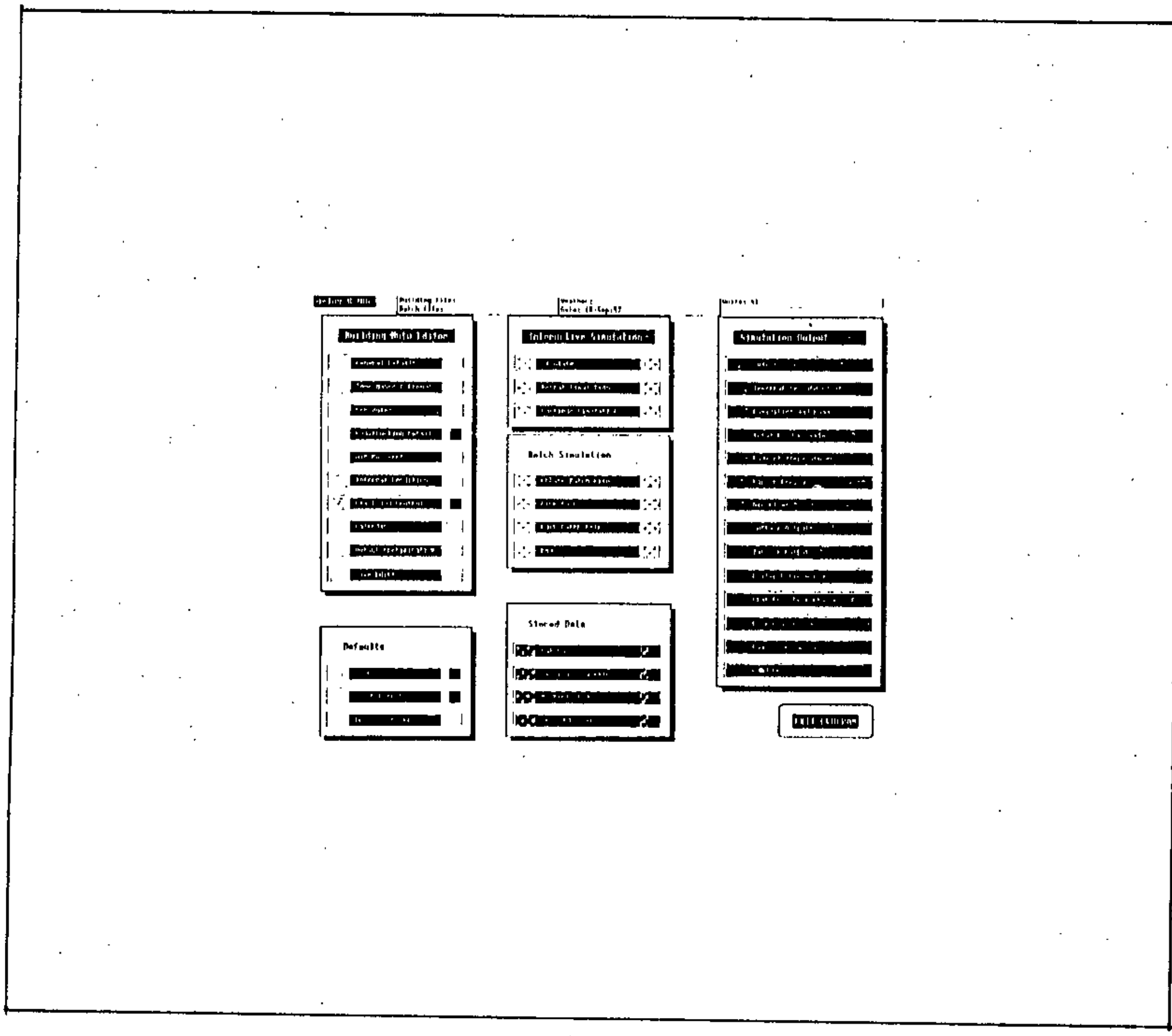
Export Data to other Programs

Control bar tool for Microsoft Excel export (.TXT format)
Lotus 1-2-3 and custom export
International data format options
Batch export utility

Other Features

Print graphs and series details
Print preview
Multiple logger launch
Long file names (up to 255 characters)
International data format options
Thumbnail view for showing many plots on screen at once

A 2.2 The Main Menu of Simulation Program ('A-Tas')



The menu system is divided into the following six sections

- Stored Data
- Building Data Editor
- Interactive Simulation
- Simulation Output
- Batch Simulation
- Defaults

The first two sections, Stored Data and Building Data Editor, contain the facilities for model creation and modification.

The following three sections, Interactive Simulation, Simulation Output and Batch Simulation, are used to do the simulations and access the resulting data.

The main purpose of the Defaults section is to allow units to be switched between Imperial and SI.

APPENDIX A 3 SIMULATION DATA

A 3.1 WEATHER DATA inputs for generating Weather File (18 June)

Date: 05:Jul:02 Time: 01:24:49

Weather File: Ban_Dhaka.wfl
Day: 169 18 June

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	1.00	27.8	89.	0.0	0.
2	0.	0.	1.00	27.7	89.	0.3	60.
3	0.	0.	1.00	27.7	89.	0.7	120.
4	0.	0.	1.00	27.6	89.	1.0	180.
5	0.	0.	1.00	27.0	92.	0.9	197.
6	0.	0.	1.00	26.4	94.	0.7	213.
7	70.	33.	1.00	25.8	97.	0.5	230.
8	628.	220.	1.00	27.2	91.	0.3	153.
9	768.	223.	1.00	28.6	86.	0.2	77.
10	977.	264.	1.00	30.0	80.	0.0	0.
11	1186.	297.	1.00	30.9	74.	0.5	17.
12	1256.	301.	1.00	31.7	68.	1.0	33.
13	1256.	314.	1.00	32.6	62.	1.5	50.
14	1116.	301.	1.00	32.9	62.	1.0	33.
15	1047.	304.	1.00	33.3	61.	0.5	17.
16	907.	318.	1.00	33.6	61.	0.0	0.
17	628.	301.	1.00	33.1	62.	0.0	0.
18	279.	179.	1.00	32.5	62.	0.0	0.
19	70.	0.	1.00	32.0	63.	0.0	0.
20	0.	0.	1.00	30.7	69.	0.3	60.
21	0.	0.	1.00	29.5	75.	0.7	120.
22	0.	0.	1.00	28.2	81.	1.0	180.
23	0.	0.	1.00	28.1	84.	0.7	120.
24	0.	0.	1.00	27.9	86.	0.3	60.

A 3.2 WEATHER DATA inputs for generating Weather File (19 June)

Date: 05:Jul:02   Time: 01:25:22

Weather File: Ban_Dhaka.wfl
Day: 170   19 June

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	1.00	27.0	90.	1.0	130.
2	0.	0.	1.00	27.2	90.	0.9	147.
3	0.	0.	1.00	27.3	89.	0.7	163.
4	0.	0.	1.00	27.5	89.	0.5	180.
5	0.	0.	1.00	27.7	87.	0.9	163.
6	0.	0.	1.00	27.8	84.	1.2	147.
7	140.	67.	1.00	28.0	82.	1.5	130.
8	558.	195.	1.00	28.9	77.	1.4	147.
9	698.	202.	1.00	29.7	72.	1.2	163.
10	1116.	301.	1.00	30.6	67.	1.0	180.
11	1256.	314.	1.00	31.1	65.	1.4	180.
12	1326.	318.	1.00	31.7	64.	1.7	180.
13	1326.	331.	1.00	32.2	62.	2.1	180.
14	1256.	339.	1.00	32.3	61.	1.9	180.
15	1186.	344.	1.00	32.3	61.	1.7	180.
16	1047.	366.	1.00	32.4	60.	1.5	180.
17	698.	335.	1.00	31.8	62.	1.7	180.
18	279.	179.	1.00	31.3	65.	1.9	180.
19	140.	0.	1.00	30.7	67.	2.1	180.
20	70.	0.	1.00	30.1	70.	1.7	163.
21	0.	0.	1.00	29.6	73.	1.4	147.
22	0.	0.	1.00	29.0	76.	1.0	130.
23	0.	0.	1.00	28.3	81.	1.0	130.
24	0.	0.	1.00	27.7	85.	1.0	130.

A 3.3 WEATHER DATA inputs for generating Weather File (20 June)

Date: 05:Jul:02 Time: 01:25:47

Weather File: Ban_Dhaka.wfl
Day: 171 20 June

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	1.00	28.0	85.	0.5	180.
2	0.	0.	1.00	27.9	86.	0.7	180.
3	0.	0.	1.00	27.7	86.	0.9	180.
4	0.	0.	1.00	27.6	87.	1.0	180.
5	0.	0.	1.00	27.6	88.	1.2	180.
6	0.	0.	1.00	27.5	88.	1.4	180.
7	70.	33.	1.00	27.5	89.	1.5	180.
8	209.	73.	1.00	28.2	85.	1.4	163.
9	628.	182.	1.00	28.9	80.	1.2	147.
10	907.	245.	1.00	29.6	76.	1.0	130.
11	907.	227.	1.00	29.5	76.	1.2	117.
12	1186.	285.	1.00	29.3	77.	1.4	103.
13	698.	174.	1.00	29.2	77.	1.5	90.
14	1326.	358.	1.00	29.5	76.	1.4	120.
15	698.	202.	1.00	29.7	74.	1.2	150.
16	279.	98.	1.00	30.0	73.	1.0	180.
17	628.	301.	1.00	29.9	74.	1.2	150.
18	419.	268.	1.00	29.7	74.	1.4	120.
19	70.	0.	1.00	29.6	75.	1.5	90.
20	0.	0.	1.00	29.4	76.	1.4	120.
21	0.	0.	1.00	29.2	78.	1.2	150.
22	0.	0.	1.00	29.0	79.	1.0	180.
23	0.	0.	1.00	28.7	81.	0.9	180.
24	0.	0.	1.00	28.3	83.	0.7	180.

A 3.4 WEATHER DATA inputs for generating Weather File (23 April)

Date: 04:Jun:02 Time: 23:57:49

Weather File: Ban_Dhaka.wfl
Day: 113 23 April

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	0.00	28.0	83.	1.5	180.
2	0.	0.	0.00	27.8	85.	1.4	180.
3	0.	0.	0.00	27.7	86.	1.2	180.
4	0.	0.	1.00	27.5	88.	1.0	180.
5	0.	0.	1.00	26.4	90.	0.7	120.
6	0.	0.	1.00	25.2	91.	0.3	60.
7	209.	107.	1.00	24.1	93.	0.0	0.
8	349.	147.	1.00	26.0	84.	0.2	60.
9	558.	190.	1.00	27.8	75.	0.3	120.
10	698.	216.	1.00	29.7	66.	0.5	180.
11	837.	234.	1.00	30.4	64.	0.9	180.
12	907.	245.	1.00	31.0	63.	1.2	180.
13	837.	234.	1.00	31.7	61.	1.5	180.
14	768.	238.	1.00	32.1	60.	1.4	180.
15	558.	190.	1.00	32.6	60.	1.2	180.
16	349.	147.	1.00	33.0	59.	1.0	180.
17	140.	71.	1.00	32.6	61.	0.7	120.
18	0.	0.	1.00	32.1	63.	0.3	60.
19	0.	0.	0.00	31.7	65.	0.0	0.
20	0.	0.	0.00	30.9	70.	0.2	43.
21	0.	0.	0.00	30.0	75.	0.3	87.
22	0.	0.	0.00	29.2	80.	0.5	130.
23	0.	0.	0.00	28.8	81.	0.9	147.
24	0.	0.	0.00	28.4	82.	1.2	163.

A 3.5 WEATHER DATA inputs for generating Weather File (24 April)

Date: 04:Jun:02 Time: 23:58:31

Weather File: Ban_Dhaka.wfl
Day: 114 24 April

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	1.00	27.4	82.	1.0	180.
2	0.	0.	1.00	27.3	84.	1.0	180.
3	0.	0.	1.00	27.1	87.	1.0	180.
4	0.	0.	1.00	27.0	89.	1.0	180.
5	0.	0.	1.00	25.7	90.	2.2	137.
6	0.	0.	1.00	24.3	90.	3.4	93.
7	70.	36.	1.00	23.0	91.	4.6	50.
8	70.	29.	1.00	22.9	86.	3.6	50.
9	907.	308.	1.00	22.9	81.	2.6	50.
10	768.	238.	1.00	22.8	76.	1.5	50.
11	837.	234.	1.00	25.2	69.	1.5	93.
12	907.	245.	1.00	27.6	62.	1.5	137.
13	907.	254.	0.00	30.0	55.	1.5	180.
14	837.	260.	0.00	30.3	55.	1.7	180.
15	698.	237.	0.00	30.7	56.	1.9	180.
16	419.	176.	0.00	31.0	56.	2.1	180.
17	0.	0.	0.00	30.6	59.	2.1	180.
18	0.	0.	0.00	30.2	63.	2.1	180.
19	0.	0.	1.00	29.8	66.	2.1	180.
20	0.	0.	0.00	29.3	70.	1.7	180.
21	0.	0.	0.00	28.9	73.	1.4	180.
22	0.	0.	0.00	28.4	77.	1.0	180.
23	0.	0.	0.00	28.1	79.	1.0	180.
24	0.	0.	1.00	27.7	80.	1.0	180.

A 3.6 WEATHER DATA inputs for generating Weather File (25 April)

Date: 04:Jun:02 Time: 23:58:59

Weather File: Ban_Dhaka.wfl
Day: 115 25 April

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	1.00	22.0	87.	1.0	130.
2	0.	0.	0.00	21.9	87.	1.0	147.
3	0.	0.	0.00	21.7	87.	1.0	163.
4	0.	0.	0.00	21.6	87.	1.0	180.
5	0.	0.	1.00	23.3	88.	0.9	180.
6	0.	0.	1.00	25.1	89.	0.7	180.
7	140.	71.	1.00	26.8	90.	0.5	180.
8	628.	264.	1.00	27.8	65.	0.9	180.
9	907.	308.	1.00	28.8	61.	1.2	180.
10	698.	216.	1.00	23.8	76.	1.5	180.
11	419.	117.	1.00	27.6	82.	1.4	150.
12	70.	19.	1.00	25.4	88.	1.2	120.
13	209.	59.	1.00	23.2	94.	1.0	90.
14	698.	216.	1.00	23.5	92.	0.9	90.
15	837.	285.	1.00	23.9	91.	0.7	90.
16	628.	264.	1.00	24.2	89.	0.5	90.
17	140.	71.	0.00	24.0	90.	0.5	90.
18	0.	0.	1.00	23.8	92.	0.5	90.
19	0.	0.	1.00	23.6	93.	0.5	90.
20	0.	0.	1.00	23.2	92.	0.7	120.
21	0.	0.	1.00	22.8	90.	0.9	150.
22	0.	0.	1.00	22.4	89.	1.0	180.
23	0.	0.	1.00	22.3	88.	1.0	163.
24	0.	0.	1.00	22.1	88.	1.0	147.

A 3.7 WEATHER DATA inputs for generating Weather File (12 May)

Date: 04:Jun:02 Time: 23:53:48

Weather File: Ban_Dhaka.wfl
Day: 132 12 May

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	0.00	29.2	71.	1.0	130.
2	0.	0.	0.00	28.7	76.	0.7	87.
3	0.	0.	0.00	28.3	80.	0.3	43.
4	0.	0.	0.00	27.8	85.	0.0	0.
5	0.	0.	0.00	26.8	86.	0.0	0.
6	0.	0.	0.00	25.8	87.	0.0	0.
7	209.	100.	1.00	24.8	88.	0.0	0.
8	488.	171.	0.00	26.8	77.	0.0	0.
9	768.	223.	0.00	28.9	65.	0.0	0.
10	907.	245.	0.00	30.9	54.	0.0	0.
11	1116.	279.	0.00	31.7	51.	0.2	90.
12	1116.	268.	0.00	32.6	48.	0.3	180.
13	1116.	279.	1.00	33.4	45.	0.5	270.
14	977.	264.	0.00	33.9	44.	0.3	180.
15	768.	223.	0.00	34.3	44.	0.2	90.
16	558.	195.	0.00	34.8	43.	0.0	0.
17	279.	134.	0.00	34.2	46.	0.0	0.
18	70.	45.	0.00	33.6	49.	0.0	0.
19	0.	0.	0.00	33.0	52.	0.0	0.
20	0.	0.	0.00	32.1	58.	0.2	43.
21	0.	0.	0.00	31.1	63.	0.3	87.
22	0.	0.	0.00	30.2	69.	0.5	130.
23	0.	0.	0.00	29.9	70.	0.7	130.
24	0.	0.	0.00	29.5	70.	0.9	130.

A 3.8 WEATHER DATA inputs for generating Weather File (13 May)

Date: 04:Jun:02 Time: 23:54:09

Weather File: Ban_Dhaka.wfl
Day: 133 13 May

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	0.00	30.0	71.	0.0	0.
2	0.	0.	0.00	29.8	74.	0.0	0.
3	0.	0.	0.00	29.6	77.	0.0	0.
4	0.	0.	0.00	29.4	80.	0.0	0.
5	0.	0.	0.00	28.8	83.	0.0	0.
6	0.	0.	0.00	28.2	87.	0.0	0.
7	349.	167.	0.00	27.6	90.	0.0	0.
8	698.	244.	0.00	29.3	82.	0.3	17.
9	977.	283.	0.00	30.9	73.	0.7	33.
10	1047.	283.	1.00	32.6	65.	1.0	50.
11	1116.	279.	1.00	32.9	62.	1.0	110.
12	1116.	268.	1.00	33.3	58.	1.0	170.
13	907.	227.	1.00	33.6	55.	1.0	230.
14	698.	188.	1.00	34.0	53.	1.0	183.
15	628.	182.	1.00	34.4	51.	1.0	137.
16	349.	122.	1.00	34.8	49.	1.0	90.
17	140.	67.	1.00	34.7	50.	0.7	60.
18	0.	0.	1.00	34.7	50.	0.3	30.
19	0.	0.	1.00	34.6	51.	0.0	0.
20	0.	0.	0.00	33.7	56.	0.0	0.
21	0.	0.	0.00	32.9	60.	0.0	0.
22	0.	0.	0.00	32.0	65.	0.0	0.
23	0.	0.	0.00	31.3	67.	0.0	0.
24	0.	0.	0.00	30.7	69.	0.0	0.

A 3.9 WEATHER DATA inputs for generating Weather File (14 May)

Date: 04:Jun:02 Time: 23:54:31

Weather File: Ban_Dhaka.wfl
Day: 134 14 May

Hour	Global Solar Radiation (W/m2)	Diffuse Solar Radiation (W/m2)	Cloud Cover (0 - 1)	Dry Bulb Temperature (C)	Relative Humidity (%)	Wind Speed (m/s)	Wind Direction (deg. E of N)
1	0.	0.	0.00	31.4	71.	1.0	180.
2	0.	0.	0.00	30.9	74.	0.7	120.
3	0.	0.	0.00	30.5	76.	0.3	60.
4	0.	0.	0.00	30.0	79.	0.0	0.
5	0.	0.	0.00	29.5	82.	0.0	0.
6	0.	0.	0.00	29.0	85.	0.0	0.
7	209.	100.	0.00	28.5	88.	0.0	0.
8	488.	171.	0.00	29.5	84.	0.3	77.
9	698.	202.	0.00	30.6	80.	0.7	153.
10	837.	226.	1.00	31.6	76.	1.0	230.
11	1116.	279.	1.00	32.7	69.	0.9	213.
12	1116.	268.	1.00	33.7	63.	0.7	197.
13	1047.	262.	1.00	34.8	56.	0.5	180.
14	837.	226.	1.00	35.3	54.	0.3	120.
15	837.	243.	1.00	35.9	53.	0.2	60.
16	628.	220.	1.00	36.4	51.	0.0	0.
17	279.	134.	1.00	36.0	53.	0.0	0.
18	140.	89.	1.00	35.7	54.	0.0	0.
19	0.	0.	1.00	35.3	56.	0.0	0.
20	0.	0.	1.00	34.4	62.	0.0	0.
21	0.	0.	1.00	33.6	67.	0.0	0.
22	0.	0.	1.00	32.7	73.	0.0	0.
23	0.	0.	0.00	32.3	72.	0.3	60.
24	0.	0.	0.00	31.8	72.	0.7	120.

A 3.10 Tabular Output of Climatic Data for Test Room without Roof Insulation (18 June)

Building Name: T2Room Building Data File: T2Room.bdf.01 Revision: 84
Time: 20:36:55 Date: 03:Jul:02 Consultant: Program: A-Tas 8.31

Zone 6 Test Room
Day 169: Tuesday, Jun 18 (WEEKDAY) Weather File: Ban_Dhaka.wfl

Time (24hr clock)	Temperature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Resultant temp. (deg C)
1	31.9	0.00	70.7	0.00	34.8	33.4
2	31.6	0.00	71.1	0.00	34.4	33.0
3	31.5	0.00	71.7	0.00	34.1	32.8
4	31.1	0.00	72.7	0.00	33.7	32.4
5	30.7	0.00	74.3	0.00	33.3	32.0
6	30.3	0.00	75.1	0.00	32.9	31.6
7	29.9	0.00	76.2	0.00	33.2	31.6
8	31.1	0.00	72.5	0.00	36.4	33.7
9	32.0	0.00	70.5	0.00	36.6	34.3
10	32.9	0.00	67.8	0.00	36.9	34.9
11	33.2	0.00	65.3	0.00	37.3	35.2
12	33.6	0.00	61.4	0.00	37.5	35.6
13	34.6	0.00	55.8	0.00	38.3	36.5
14	34.7	0.00	55.9	0.00	38.8	36.8
15	35.3	0.00	54.6	0.00	39.4	37.3
16	36.1	0.00	53.0	0.00	40.1	38.1
17	36.1	0.00	52.6	0.00	40.6	38.3
18	35.9	0.00	51.6	0.00	40.3	38.1
19	35.5	0.00	52.1	0.00	38.8	37.1
20	34.6	0.00	55.2	0.00	38.2	36.4
21	33.8	0.00	58.5	0.00	37.7	35.8
22	32.8	0.00	62.3	0.00	37.0	34.9
23	32.7	0.00	64.3	0.00	36.5	34.6
24	32.4	0.00	66.3	0.00	36.0	34.2

A 3.11 Tabular Output of Climatic Data for Test Room without Roof Insulation (19 June)

Building Name: T2Room Building Data File: T2Room.bdf.01 Revision: 84
Time: 20:37:36 Date: 03:Jul:02 Consultant: Program: A-Tas 8.31

Zone 6 Test Room
Day 170: Wednesday, Jun 19 (WEEKDAY) Weather File: Ban_Dhaka.wfl

Time (24hr clock)	Temperature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Resultant temp. (deg C)
1	31.8	0.00	68.4	0.00	35.4	33.6
2	31.6	0.00	69.6	0.00	34.9	33.3
3	31.5	0.00	69.9	0.00	34.5	33.0
4	31.4	0.00	70.8	0.00	34.2	32.8
5	31.4	0.00	70.5	0.00	33.8	32.6
6	31.3	0.00	68.9	0.00	33.5	32.4
7	31.4	0.00	67.4	0.00	34.5	33.0
8	32.3	0.00	63.6	0.00	36.7	34.5
9	32.8	0.00	60.6	0.00	36.9	34.8
10	33.3	0.00	57.7	0.00	37.7	35.5
11	33.3	0.00	57.5	0.00	37.9	35.6
12	33.6	0.00	57.5	0.00	38.0	35.8
13	33.8	0.00	56.7	0.00	38.5	36.2
14	34.1	0.00	55.1	0.00	39.1	36.6
15	34.5	0.00	54.1	0.00	39.6	37.0
16	35.0	0.00	52.1	0.00	40.2	37.6
17	34.7	0.00	52.6	0.00	40.4	37.6
18	34.4	0.00	54.7	0.00	39.7	37.0
19	33.7	0.00	56.6	0.00	38.0	35.8
20	33.9	0.00	56.5	0.00	37.4	35.7
21	33.6	0.00	58.1	0.00	36.9	35.2
22	33.2	0.00	59.9	0.00	36.4	34.8
23	32.6	0.00	63.1	0.00	35.9	34.3
24	32.1	0.00	65.8	0.00	35.4	33.8

A 3.12 Tabular Output of Climatic Data for Test Room without Roof Insulation (20 June)

Building Name: T2Room   Building Data File: T2Room.bdf.01   Revision: 84
Time: 20:38:19 Date: 03:Jul:02   Consultant: Program: A-Tas 8.31

Zone 6 Test Room
Day 171: Thursday, Jun 20 (WEEKDAY) Weather File: Ban_Dhaka.wfl

Time (24hr clock)	Temperature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Resultant temp. (deg C)
1	32.1	0.00	67.2	0.00	35.0	33.5
2	31.8	0.00	68.6	0.00	34.6	33.2
3	31.5	0.00	69.1	0.00	34.2	32.9
4	31.3	0.00	70.3	0.00	33.9	32.6
5	31.1	0.00	71.9	0.00	33.5	32.3
6	30.8	0.00	72.7	0.00	33.2	32.0
7	30.7	0.00	73.9	0.00	33.5	32.1
8	31.3	0.00	71.1	0.00	34.1	32.7
9	32.0	0.00	67.2	0.00	35.7	33.8
10	32.5	0.00	64.4	0.00	36.2	34.4
11	32.4	0.00	64.5	0.00	36.0	34.2
12	32.3	0.00	64.8	0.00	36.4	34.4
13	32.2	0.00	65.1	0.00	36.0	34.1
14	32.7	0.00	63.4	0.00	37.4	35.0
15	32.9	0.00	61.9	0.00	36.9	34.9
16	33.0	0.00	61.5	0.00	36.5	34.7
17	33.3	0.00	61.0	0.00	37.8	35.5
18	33.3	0.00	60.4	0.00	38.2	35.7
19	32.8	0.00	62.4	0.00	36.0	34.4
20	32.7	0.00	62.9	0.00	35.5	34.1
21	32.5	0.00	64.4	0.00	35.2	33.8
22	32.2	0.00	65.7	0.00	34.8	33.5
23	32.0	0.00	67.1	0.00	34.4	33.2
24	31.7	0.00	68.4	0.00	34.1	32.9

A 3.13 Performance Summary of Test Room without Roof Insulation

Building Name: T2Room   Building Data File: T2Room.bdf.01   Revision: 84
Time: 20:39:21 Date: 03:Jul:02   Consultant: Program: A-Tas 8.31

Day 169 to DAY 172
Weather File: Ban_Dhaka.wfl

INTERNAL CONDITIONS		Max/Min value	During day	At hour	In Zone
Max. air temperature	(deg C)	37.1	169	17	8
Min. air temperature	(deg C)	27.9	172	7	2
Max. humidity	(%)	83.1	169	7	2
Min. humidity	(%)	47.9	170	16	8
Max. heating load	(kW)	0.00	0	0	0
Max. cooling load	(kW)	0.00	0	0	0
Max. latent addition	(kW)	0.00	0	0	0
Max. latent removal	(kW)	0.00	0	0	0
Max. resultant temperature	(deg C)	39.4	169	16	7
Min. resultant temperature	(deg C)	29.4	172	6	7
Max. mean radiant temperature	(deg C)	43.3	170	16	7
Min. mean radiant temperature	(deg C)	30.7	172	6	7

EXTERNAL CONDITIONS		Max/Min value	During day	At hour
Max. dry bulb temperature	(deg C)	33.6	169	16
Min. dry bulb temperature	(deg C)	25.0	172	7
Max. humidity	(%)	97.0	169	7
Min. humidity	(%)	60.0	170	16

A 3.14 Tabular Output of Climatic Data for Test Room with Roof Insulation at 500mm (23 April)

Building Name: T1Room Building Data File: T1Room.bdf.01 Revision: 81
Time: 13:11:48 Date: 29:Mar:02 Program: A-Tas 8.31
Zone 6 Test Room
Day 113: Tuesday, Apr 23 (WEEKDAY) Weather File: Ban_Dhaka.wfl

Time (24hr clock)	Temperature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Resultant temp. (deg C)
1	28.1	0.00	82.5	0.00	29.4	28.7
2	27.9	0.00	84.4	0.00	29.4	28.7
3	27.8	0.00	85.3	0.00	29.4	28.6
4	27.6	0.00	87.2	0.00	29.3	28.5
5	26.6	0.00	88.9	0.00	29.1	27.9
6	25.5	0.00	89.4	0.00	28.8	27.2
7	24.6	0.00	90.5	0.00	30.6	27.6
8	26.3	0.00	82.6	0.00	31.2	28.8
9	28.0	0.00	74.2	0.00	32.0	30.0
10	29.8	0.00	65.7	0.00	32.1	31.0
11	30.4	0.00	63.9	0.00	32.1	31.2
12	31.0	0.00	63.0	0.00	32.3	31.7
13	31.7	0.00	61.1	0.00	32.4	32.0
14	32.1	0.00	60.1	0.00	32.7	32.4
15	32.5	0.00	60.2	0.00	32.7	32.6
16	33.0	0.00	59.1	0.00	32.7	32.9
17	32.6	0.00	61.0	0.00	32.4	32.5
18	32.1	0.00	62.9	0.00	32.0	32.1
19	31.8	0.00	64.8	0.00	31.9	31.8
20	31.0	0.00	69.6	0.00	31.8	31.4
21	30.1	0.00	74.4	0.00	31.7	30.9
22	29.4	0.00	79.1	0.00	31.5	30.5
23	29.0	0.00	80.0	0.00	31.4	30.2
24	28.6	0.00	80.9	0.00	31.2	29.9

A 3.15 Tabular Output of Climatic Data for Test Room with Roof Insulation at 500mm (24 April)

Building Name: T1Room Building Data File: T1Room.bdf.01 Revision: 81
Time: 13:28:49 Date: 29:Mar:02 Program: A-Tas 8.31
Zone 6 Test Room
Day 114: Wednesday, Apr 24 (WEEKDAY) Weather File: Ban_Dhaka.wfl

Time (24hr clock)	Temperature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Resultant temp. (deg C)
1	27.7	0.00	80.6	0.00	31.0	29.3
2	27.6	0.00	82.5	0.00	30.8	29.2
3	27.4	0.00	85.4	0.00	30.6	29.0
4	27.3	0.00	87.4	0.00	30.5	28.9
5	26.1	0.00	88.0	0.00	30.1	28.1
6	24.6	0.00	88.4	0.00	29.6	27.1
7	23.4	0.00	88.9	0.00	29.8	26.6
8	23.3	0.00	84.0	0.00	29.3	26.3
9	23.4	0.00	78.5	0.00	32.8	28.1
10	23.4	0.00	73.4	0.00	31.3	27.4
11	25.5	0.00	67.9	0.00	31.0	28.2
12	27.8	0.00	61.4	0.00	31.4	29.6
13	30.0	0.00	55.0	0.00	31.7	30.9
14	30.3	0.00	54.9	0.00	32.0	31.2
15	30.7	0.00	55.9	0.00	32.2	31.4
16	31.0	0.00	55.8	0.00	32.1	31.6
17	30.7	0.00	58.8	0.00	31.1	30.9
18	30.3	0.00	62.7	0.00	31.0	30.6
19	29.9	0.00	65.6	0.00	30.9	30.4
20	29.4	0.00	69.5	0.00	30.8	30.1
21	29.1	0.00	72.4	0.00	30.7	29.9
22	28.6	0.00	76.2	0.00	30.6	29.6
23	28.3	0.00	78.1	0.00	30.5	29.4
24	27.9	0.00	79.0	0.00	30.3	29.1

A 3.16 Tabular Output of Climatic Data for Test Room with Roof Insulation at 500mm (25 April)

Building Name: T1Room Building Data File: T1Room.bdf.01 Revision: 81
Time: 13:35:09 Date: 29:Mar:02 Program: A-Tas 8.31
Zone 6 Test Room
Day 115: Thursday, Apr 25 (WEEKDAY) Weather File: Ban_Dhaka.wfl

Time (24hr clock)	Temperature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Resultant temp. (deg C)
1	22.7	0.00	83.5	0.00	29.3	26.0
2	22.5	0.00	83.6	0.00	28.8	25.7
3	22.3	0.00	83.7	0.00	28.4	25.4
4	22.2	0.00	83.8	0.00	28.0	25.1
5	23.7	0.00	85.8	0.00	28.1	25.9
6	25.3	0.00	87.7	0.00	28.2	26.8
7	27.0	0.00	89.1	0.00	29.8	28.4
8	28.0	0.00	84.0	0.00	32.9	30.5
9	29.0	0.00	80.1	0.00	33.7	31.3
10	29.9	0.00	75.6	0.00	32.3	31.1
11	27.8	0.00	81.0	0.00	30.9	29.3
12	25.7	0.00	86.4	0.00	29.7	27.7
13	23.7	0.00	91.4	0.00	29.3	26.5
14	23.9	0.00	89.7	0.00	30.1	27.0
15	24.3	0.00	88.8	0.00	30.6	27.4
16	24.6	0.00	86.7	0.00	30.6	27.6
17	24.4	0.00	87.7	0.00	29.4	26.9
18	24.2	0.00	89.7	0.00	28.8	26.5
19	24.0	0.00	90.7	0.00	28.5	26.3
20	23.6	0.00	89.6	0.00	28.3	26.0
21	23.3	0.00	87.5	0.00	28.0	25.6
22	22.9	0.00	86.4	0.00	27.7	25.3
23	22.8	0.00	85.6	0.00	27.5	25.1
24	22.6	0.00	85.6	0.00	27.3	24.9

A 3.17 Performance Summary of Test Room for Test Room with Roof Insulation at 500mm

Building Name: T1Room Building Data File: T1Room.bdf.01 Revision: 81
Time: 13:35:37 Date: 29:Mar:02 Program: A-Tas 8.31

Day 111 to DAY 115
Weather File: Ban_Dhaka.wfl

INTERNAL CONDITIONS		Max/Min value	During day	At hour	In Zone
Max. air temperature	(deg C)	33.2	111	16	8
Min. air temperature	(deg C)	21.6	112	7	7
Max. humidity	(%)	92.6	115	13	7
Min. humidity	(%)	44.9	111	16	8
Max. heating load	(kW)	0.00	0	0	0
Max. cooling load	(kW)	0.00	0	0	0
Max. latent addition	(kW)	0.00	0	0	0
Max. latent removal	(kW)	0.00	0	0	0
Max. resultant temperature	(deg C)	35.6	111	8	2
Min. resultant temperature	(deg C)	24.5	115	4	7
Max. mean radiant temperature	(deg C)	45.8	111	8	7
Min. mean radiant temperature	(deg C)	26.6	115	24	7

EXTERNAL CONDITIONS				
Max. dry bulb temperature	(deg C)	33.2	111	16
Min. dry bulb temperature	(deg C)	21.2	111	10
Max. humidity	(%)	96.0	111	10
Min. humidity	(%)	45.0	111	16

A 3.18 Tabular Output of Climatic Data for Test Room with Roof Insulation at 200mm (12 May)

Building Name: T3 Room   Building Data File: T3.bdf.01   Revision: 84
Time: 23:09:37 Date: 04:Jun:02   Program: A-Tas 8.31
Zone 6 Test Room
Day 132: Sunday, May 12 (SUNDAY)   Weather File: Ban_Dhaka.wf1

Time (24hr clock)	Temper-ature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Result-ant temp. (deg C)
1	29.4	0.00	70.1	0.00	32.1	30.8
2	29.0	0.00	74.9	0.00	32.0	30.5
3	28.6	0.00	78.7	0.00	31.8	30.2
4	28.1	0.00	83.4	0.00	31.6	29.9
5	27.2	0.00	84.1	0.00	31.3	29.2
6	26.3	0.00	84.7	0.00	30.9	28.6
7	25.4	0.00	85.0	0.00	32.5	28.9
8	27.2	0.00	75.1	0.00	33.9	30.6
9	29.2	0.00	64.0	0.00	34.8	32.0
10	31.0	0.00	53.6	0.00	34.7	32.9
11	31.8	0.00	50.8	0.00	34.8	33.3
12	32.6	0.00	47.9	0.00	34.8	33.7
13	33.4	0.00	45.0	0.00	35.1	34.3
14	33.9	0.00	44.0	0.00	35.3	34.6
15	34.3	0.00	44.0	0.00	35.4	34.8
16	34.8	0.00	43.0	0.00	35.5	35.2
17	34.3	0.00	45.8	0.00	35.3	34.8
18	33.7	0.00	48.7	0.00	34.9	34.3
19	33.1	0.00	51.7	0.00	34.4	33.8
20	32.3	0.00	57.4	0.00	34.3	33.3
21	31.3	0.00	62.1	0.00	34.0	32.7
22	30.5	0.00	67.8	0.00	33.8	32.1
23	30.2	0.00	68.8	0.00	33.5	31.9
24	29.8	0.00	68.8	0.00	33.3	31.6

A 3.19 Tabular Output of Climatic Data for Test Room with Roof Insulation at 200mm (13 May)

Building Name: T3 Room Building Data File: T3.bdf.01 Revision: 84
Time: 23:15:02 Date: 04:Jun:02 Program: A-Tas 8.31
Zone 6 Test Room
Day 133: Monday, May 13 (WEEKDAY) Weather File: Ban_Dhaka.wfl

Time (24hr clock)	Temperature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Resultant temp. (deg C)
1	30.3	0.00	69.9	0.00	33.2	31.7
2	30.1	0.00	72.8	0.00	33.1	31.6
3	29.9	0.00	75.8	0.00	32.9	31.4
4	29.7	0.00	78.7	0.00	32.8	31.2
5	29.1	0.00	81.5	0.00	32.6	30.8
6	28.6	0.00	85.2	0.00	32.3	30.4
7	28.1	0.00	87.4	0.00	35.2	31.7
8	29.7	0.00	90.1	0.00	36.9	33.3
9	31.2	0.00	71.7	0.00	37.4	34.3
10	32.8	0.00	64.4	0.00	37.0	34.9
11	33.0	0.00	61.6	0.00	36.6	34.8
12	33.4	0.00	57.6	0.00	36.5	34.9
13	33.7	0.00	54.7	0.00	36.3	35.0
14	34.1	0.00	52.8	0.00	36.3	35.2
15	34.5	0.00	50.8	0.00	36.4	35.5
16	34.9	0.00	48.8	0.00	36.3	35.6
17	34.8	0.00	49.8	0.00	36.1	35.4
18	34.8	0.00	49.8	0.00	35.7	35.2
19	34.7	0.00	50.8	0.00	35.7	35.2
20	33.8	0.00	55.5	0.00	35.5	34.7
21	33.1	0.00	59.3	0.00	35.3	34.2
22	32.3	0.00	64.1	0.00	35.1	33.7
23	31.6	0.00	65.9	0.00	34.8	33.2
24	31.0	0.00	67.7	0.00	34.6	32.8

A 3.20 Tabular Output of Climatic Data for Test Room with Roof Insulation at 200mm (14 May)

Building Name: T3 Room Building Data File: T3.bdf.01 Revision: 84
Time: 23:20:22 Date: 04:Jun:02 Program: A-Tas 8.31
Zone 6 Test Room
Day 134: Tuesday, May 14 (WEEKDAY) Weather File: Ban_Dhaka.wf1

Time (24hr clock)	Temperature (deg C)	Sensible load (kW)	Humidity (%)	Latent load (kW)	Mean radiant temp. (deg C)	Resultant temp. (deg C)
1	31.7	0.00	70.0	0.00	34.5	33.1
2	31.2	0.00	72.8	0.00	34.3	32.7
3	30.8	0.00	74.7	0.00	34.1	32.5
4	30.3	0.00	77.5	0.00	33.9	32.1
5	29.9	0.00	80.3	0.00	33.6	31.7
6	29.4	0.00	83.2	0.00	33.4	31.4
7	29.0	0.00	85.6	0.00	35.0	32.0
8	29.9	0.00	82.0	0.00	36.3	33.1
9	30.9	0.00	78.4	0.00	36.7	33.8
10	31.9	0.00	74.8	0.00	36.6	34.2
11	32.9	0.00	68.4	0.00	36.8	34.8
12	33.8	0.00	62.6	0.00	36.8	35.3
13	34.9	0.00	55.9	0.00	37.0	35.9
14	35.3	0.00	53.9	0.00	37.1	36.2
15	35.9	0.00	52.9	0.00	37.5	36.7
16	36.4	0.00	50.9	0.00	37.7	37.1
17	36.1	0.00	52.8	0.00	37.4	36.8
18	35.8	0.00	53.7	0.00	37.4	36.6
19	35.4	0.00	55.7	0.00	36.7	36.1
20	34.6	0.00	61.4	0.00	36.5	35.6
21	33.8	0.00	66.1	0.00	36.4	35.1
22	33.0	0.00	71.8	0.00	36.1	34.6
23	32.6	0.00	70.8	0.00	35.9	34.3
24	32.1	0.00	70.7	0.00	35.7	33.9

A 3.21 Performance Summary of Test Room with Insulation at 200mm

Building Name: T3 Room — Building Data File: T3.bdf.01 — Revision: 84
Time: 23:20:41 Date: 04:Jun:02 — Program: A-Tas 8.31

Day 130 to DAY 134
Weather File: Ban_Dhaka.wfl

INTERNAL CONDITIONS		Max/Min value	During day	At hour	In Zone
Max. air temperature	(deg C)	36.6	134	16	8
Min. air temperature	(deg C)	25.1	132	7	7
Max. humidity	(%)	92.7	130	7	7
Min. humidity	(%)	42.8	132	16	8
Max. heating load	(kW)	0.00	0	0	0
Max. cooling load	(kW)	0.00	0	0	0
Max. latent addition	(kW)	0.00	0	0	0
Max. latent removal	(kW)	0.00	0	0	0
Max. resultant temperature	(deg C)	38.7	134	16	7
Min. resultant temperature	(deg C)	27.7	131	4	7
Max. mean radiant temperature	(deg C)	44.5	133	9	7
Min. mean radiant temperature	(deg C)	29.6	131	6	2
EXTERNAL CONDITIONS					
Max. dry bulb temperature	(deg C)	36.4	134	16	
Min. dry bulb temperature	(deg C)	24.8	132	7	
Max. humidity	(%)	94.0	130	7	
Min. humidity	(%)	43.0	132	16	

A 3.22 Simulation Output of Ceiling and Globe Temperature (in deg C) at different height of Insulation

Date	Time	Uninsulated Ceiling	Uninsulated Globe	50 mm Ceiling	50 mm Globe	100 mm Ceiling	100 mm Globe	200 mm Ceiling	200 mm Globe	500 mm Ceiling	500 mm Globe	1000 mm Ceiling	1000 mm Globe
23-Apr	1:00 AM	35.6	34.8	30.4	29.4	30.4	29.4	30.4	29.4	30.5	29.4	30.4	29.4
	2:00 AM	35	34.4	30.4	29.4	30.4	29.4	30.4	29.4	30.4	29.4	30.4	29.4
	3:00 AM	34.3	34.1	30.3	29.3	30.3	29.3	30.3	29.3	30.3	29.4	30.3	29.3
	4:00 AM	33.7	33.7	30.1	29.3	30.1	29.3	30.1	29.3	30.2	29.3	30.1	29.3
	5:00 AM	33.2	33.3	30	29.1	30	29.1	30	29.1	30	29.1	30	29.1
	6:00 AM	32.6	32.9	29.8	28.8	29.8	28.8	29.8	28.8	29.8	28.8	29.8	28.8
	7:00 AM	32.2	33.2	29.9	30.5	29.9	30.5	29.9	30.5	29.9	30.6	29.9	30.5
	8:00 AM	32.7	36.4	30.2	31.2	30.2	31.2	30.2	31.2	30.2	31.2	30.2	31.2
	9:00 AM	33.8	36.6	30.5	32	30.5	32	30.5	32	30.5	32	30.5	32
	10:00 AM	35.2	36.9	30.9	32.1	30.9	32.1	30.9	32.1	30.9	32.1	30.9	32.1
	11:00 AM	37	37.3	31.3	32.1	31.2	32	31.2	32	31.3	32.1	31.2	32
	12:00 PM	36.8	37.5	31.6	32.3	31.6	32.3	31.6	32.3	31.6	32.3	31.6	32.3
	1:00 PM	40.4	38.3	32	32.4	32	32.4	32	32.4	32	32.4	32	32.3
	2:00 PM	41.8	38.8	32.3	32.7	32.3	32.7	32.3	32.7	32.3	32.7	32.3	32.7
	3:00 PM	42.9	39.4	32.6	32.7	32.6	32.7	32.6	32.7	32.6	32.7	32.6	32.7
	4:00 PM	44	40.1	32.9	32.7	32.8	32.7	32.8	32.7	32.8	32.7	32.8	32.7
	5:00 PM	44.8	40.6	32.9	32.4	32.9	32.4	32.9	32.4	32.9	32.4	32.9	32.4
	6:00 PM	44.9	40.3	32.9	32	32.9	32	32.9	32	32.9	32	32.8	32
	7:00 PM	44.1	38.8	32.8	31.9	32.8	31.9	32.8	31.9	32.8	31.9	32.8	31.9
	8:00 PM	42.8	38.2	32.7	31.8	32.7	31.8	32.7	31.8	32.7	31.8	32.7	31.8
	9:00 PM	41.4	37.7	32.6	31.7	32.5	31.7	32.5	31.7	32.5	31.7	32.5	31.7
	10:00 PM	40	37	32.4	31.5	32.4	31.5	32.4	31.5	32.4	31.5	32.4	31.5
	11:00 PM	38.7	38.5	32.2	31.4	32.2	31.4	32.2	31.4	32.2	31.4	32.2	31.3
	12:00 AM	37.6	36	32.1	31.2	32.1	31.2	32.1	31.2	32.1	31.2	32.1	31.2
24-Apr	1:00 AM	36.6	35.4	31.9	31	31.9	30.9	31.9	30.9	31.9	31	31.9	30.9
	2:00 AM	35.7	34.9	31.7	30.8	31.7	30.8	31.7	30.8	31.7	30.8	31.7	30.8
	3:00 AM	34.9	34.5	31.5	30.6	31.5	30.6	31.5	30.6	31.5	30.8	31.5	30.6
	4:00 AM	34.2	34.2	31.4	30.5	31.4	30.4	31.4	30.4	31.4	30.5	31.4	30.4
	5:00 AM	33.6	33.8	31.1	30.1	31.1	30.1	31.1	30.1	31.1	30.1	31.1	30.1
	6:00 AM	33.1	33.5	30.9	29.6	30.8	29.6	30.8	29.6	30.9	29.6	30.8	29.6
	7:00 AM	32.9	34.5	30.6	29.6	30.6	29.8	30.6	29.6	30.6	29.6	30.6	29.6
	8:00 AM	33.4	36.7	30.4	29.3	30.4	29.3	30.3	29.3	30.4	29.3	30.3	29.3
	9:00 AM	34.2	36.9	30.8	32.6	30.8	32.6	30.8	32.6	30.6	32.8	30.6	32.6
	10:00 AM	35.5	37.7	30.6	31.3	30.8	31.3	30.8	31.3	30.8	31.3	30.8	31.3

Continuation of A 3.22

Date	Time	Uninsulated Ceiling	Uninsulated Globe	50 mm Ceiling	50 mm Globe	100 mm Ceiling	100 mm Globe	200 mm Ceiling	200 mm Globe	500 mm Ceiling	500 mm Globe	1000 mm Ceiling	1000 mm Globe
	11:00 AM	37.1	37.9	30.9	31	30.9	31	30.9	31	30.9	31	30.9	31
	12:00 PM	38.8	38	31.2	31.4	31.2	31.4	31.2	31.4	31.2	31.4	31.2	31.4
	1:00 PM	40.3	38.5	31.6	31.7	31.5	31.7	31.5	31.7	31.5	31.7	31.5	31.7
	2:00 PM	41.5	39.1	31.9	32	31.9	32	31.9	32	31.9	32	31.9	32
	3:00 PM	42.6	39.6	32.2	32.2	32.1	32.2	32.1	32.2	32.1	32.2	32.1	32.2
	4:00 PM	43.4	40.2	32.3	32.1	32.3	32.1	32.3	32.1	32.3	32.1	32.3	32.1
	5:00 PM	43.9	40.4	32.3	31.1	32.2	31.1	32.2	31.1	32.2	31.1	32.2	31
	6:00 PM	43.6	39.7	32.1	31	32.1	31	32.1	31	32.1	31	32.1	31
	7:00 PM	42.4	38	32	30.9	32	30.9	32	30.9	32	30.9	32	30.9
	8:00 PM	40.9	37.4	31.9	30.8	31.9	30.8	31.8	30.8	31.8	30.8	31.8	30.8
	9:00 PM	39.6	36.9	31.7	30.7	31.7	30.7	31.7	30.7	31.7	30.7	31.7	30.7
	10:00 PM	38.4	36.4	31.6	30.6	31.6	30.6	31.5	30.6	31.6	30.6	31.5	30.6
	11:00 PM	37.3	35.9	31.4	30.5	31.4	30.4	31.4	30.4	31.4	30.5	31.4	30.4
	12:00 AM	36.4	35.4	31.3	30.3	31.2	30.3	31.2	30.3	31.2	30.3	31.2	30.3
25-Apr	1:00 AM	35.5	35	30.8	29.3	30.8	29.3	30.8	29.3	30.8	29.3	30.8	29.3
	2:00 AM	34.8	34.6	30.4	28.8	30.4	28.8	30.4	28.8	30.4	28.3	30.4	28.8
	3:00 AM	34.2	34.2	30	28.4	30	28.4	30	28.4	30	28.4	30	28.4
	4:00 AM	33.6	33.9	29.7	28	29.7	28	29.7	28	29.7	28	29.7	28
	5:00 AM	33.1	33.5	29.5	28.1	29.5	28.1	29.5	28.1	29.5	28.1	29.5	28.1
	6:00 AM	32.6	33.2	29.4	28.2	29.4	28.2	29.4	28.2	29.4	28.2	29.4	28.2
	7:00 AM	32.3	33.5	29.6	29.8	29.6	29.8	29.6	29.8	29.6	29.8	29.6	29.8
	8:00 AM	32.3	34.1	30.2	32.9	30.2	32.9	30.2	32.9	30.3	32.9	30.2	32.9
	9:00 AM	32.8	35.7	30.9	33.7	30.9	33.7	30.9	33.7	30.9	33.7	30.9	33.7
	10:00 AM	33.9	36.2	31.1	32.3	31.1	32.3	31.1	32.3	31.1	32.3	31.1	32.3
	11:00 AM	35.2	36	31	30.9	31	30.9	31	30.9	31	30.9	31	30.9
	12:00 PM	36.5	36.4	30.8	29.7	30.8	29.7	30.8	29.6	30.8	27.7	30.8	29.6
	1:00 PM	37.6	36	30.5	29.3	30.5	29.3	30.5	29.3	30.5	29.3	30.5	29.3
	2:00 PM	38.5	37.4	30.5	30.1	30.5	30.1	30.5	30.1	30.5	30.1	30.5	30.1
	3:00 PM	39.5	36.9	30.7	30.8	30.7	30.8	30.6	30.6	30.6	30.6	30.6	30.6
	4:00 PM	39.7	36.5	30.9	30.6	30.9	30.6	30.6	30.6	30.8	30.6	30.8	30.6
	5:00 PM	39.6	37.8	30.8	29.4	30.6	29.3	30.8	29.3	30.8	29.4	30.7	29.3
	6:00 PM	39.7	34.4	30.5	28.8	30.5	28.7	30.5	28.7	30.5	28.8	30.5	28.7
	7:00 PM	39.1	34.1	30.3	28.5	30.3	28.5	30.3	28.5	30.3	28.5	30.3	28.5
	8:00 PM	38	35.5	30	28.3	30	28.3	30	28.3	30	28.3	30	28.3
	9:00 PM	37	35.2	29.7	28	29.7	28	29.7	28	29.7	28	29.7	28
	10:00 PM	36.2	34.8	29.5	27.7	29.4	27.7	29.4	27.7	29.4	27.7	29.4	27.7
	11:00 PM	35.4	34.4	29.2	27.5	29.2	27.5	29.2	27.5	29.2	27.5	29.2	27.5
	12:00 AM	34.7	34.1	28.9	27.3	28.9	27.3	28.9	27.3	28.9	27.3	28.9	27.3

A-3.23 Particulars of Test Rooms

Particulars of Test Room discussed about the general details if test rooms, how they are zoned, what building elements are assigned to them, what are the materials used in construction, aperture types etc.

a) General Details

Building Name: T1Room Building Data File: T1Room.bdf.01 Revision: 81

Time: 23:58:41 Date: 23:Mar:02 Program: A-Tas 8.31

Date created: 17:Jan:02	Date last modified: 15:Mar:02

Building Name:	T1 Room	17:Jan:02
Client:	Architecture Dept. BUET	
Engineer (1):	Mozammel H Mridha	
Engineer (2):		

Number of Zones:	10
Number of Building Elements:	19
Number of Apertures:	24
Number of Preconditioning Days:	10

Default weather file: Ban_Dhaka.wfl

Ground Solar Reflectance:	0.200
Building Height (m):	5.84
Building Height Adjustment Factor:	1.000
Mean Height of Surroundings (m):	6.00
Terrain Type:	City

Building Description:

"A Test Room on top floor of a 4 storied building with Roof Insulation at 500 mm above the Roof"

Building Name: T2Room Building Data File: T2Room.bdf.01 Revision: 84
Time: 00:14:00 Date: 24:Mar:02 Program: A-Tas 8.31

Date created: 17:Jan:02	Date last modified: 15:Mar:02

Building Name:	T2 Room 17:Jan:02
Client:	Architecture Dept. BUET
Engineer (1):	Mozammel H Mridha
Engineer (2):	

Number of Zones:	10
Number of Building Elements:	19
Number of Apertures:	18
Number of Preconditioning Days:	10

Default weather file: Ban_Dhaka.wfl

Ground Solar Reflectance:	0.200
Building Height (m):	5.84
Building Height Adjustment Factor:	1.000
Mean Height of Surroundings (m):	6.00
Terrain Type:	City

Building Description:

"A Test Room on top floor of a 4 storied building without Roof Insulation"

Building Name: T3 Room Building Data File: T3.bdf.01 Revision: 84
Time: 23:02:55 Date: 04:Jun:02 Program: A-Tas 8.31

Date created: 17:Jan:02	Date last modified: 04:Jun:02

Building Name:	T3 Room 17:Jan:02
Client:	Architecture Dept. BUET
Engineer (1):	Mozammel H Mridha
Engineer (2):	

Number of Zones:	10
Number of Building Elements:	19
Number of Apertures:	24
Number of Preconditioning Days:	10

Default weather file: Ban_Dhaka.wfl

Ground Solar Reflectance:	0.200
Building Height (m):	5.84
Building Height Adjustment Factor:	1.000
Mean Height of Surroundings (m):	6.00
Terrain Type:	City

Building Description:

"A Test Room on top floor of a 4 storied building with Roof Insulation at 200mm above the Roof"

b) Zone Names & Groups

Building Name: T1Room   Building Data File: T1Room.bdf.01   Revision: 81
Time: 00:09:48   Date: 24:Mar:02   Program: A-Tas 8.31

Zone Number	Zone Name	Zone Group Membership abcdefghijklmnopqrstuvwxyzABCD
1	Bed Room	a-----------------------------
2	Balcony	a-----------------------------
3	Living Room	a-----------------------------
4	Foyer	a-----------------------------
5	Toilet	a-----------------------------
6	Test Room	-b----------------------------
7	Balcony (TF)	-b----------------------------
8	Living Room (TF)	-b----------------------------
9	Foyer (TF)	-b----------------------------
10	Toilet (TF)	-b----------------------------

	Zone Group Name
a	Ground Floor
b	Test Floor
c	
d	
e	
f	
g	
h	
i	
j	
k	
l	
m	
n	
o	
p	
q	
r	
s	
t	
u	
v	
w	
x	
y	
z	
A	
B	

c) Building Elements

Building Name: T1Room Building Data File: T1Room.bdf.01 Revision: 81
Time: 20:50:59 Date: 23:Mar:02 Program: A-Tas 8.31

Building Element	C-Code	Construction name	Subst. Bldg. El.	Subst. Sched.	Shad. Feat. No.
1. Ground Floor	ground/1	Ground floor no false floor	0	0	0
2. Internal Wall	wall/1	wall	0	0	0
3. External Wall	wall/1	wall	0	0	0
4. Ceiling /Upper Floor	ceiling6/1	ceiling	0	0	0
5. w1	glass/5	window glass	0	0	1
6. Ceiling	ceiling/5	ceiling	0	0	0
7. hw	glass/5	window glass	0	0	0
8. Internal Wall-1	intwall/1	wall	0	0	0
9. w2	glass/5	window glass	0	0	2
10. d1	door/2	door	0	0	0
11. w3	glass/5	window glass	0	0	3
12. w4	glass/5	window glass	0	0	4
13. w5	glass/5	window glass	0	0	5
15. w6	glass/5	window glass	0	0	6
15. d2	door/2	door	0	0	0

d) Construction Details

Time Now	Date	Program
12:27:28	24:Feb:02	A-Tas 8.31

DATABASE CONSTRUCTION

C-Code: ground/1	Construction name: Ground floor no false floor

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.760	0.500	0.910	0.900	0.297	128.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1tile/8 PLASTIC *3	5.00	0.500	1050.0	837.0	-	99.000
2	am1concd/9 CONCRETE SCREED *3	50.00	1.280	2100.0	1000.0	-	34.000
3	am1concd/1 CONCRETE 3% m.c. 8 *3	125.00	0.870	1800.0	920.0	-	14.800
4	amlaggr/4 CRUSHED BRICK AGGREGATE *1	75.00	0.550	1580.0	1057.0	-	12.000
5	am1soil/7 SAND, DRY *2	1000.00	0.329	1515.0	796.0	-	99.000

U VALUES (W/m2K): 0.282 (Wall) 0.284 (Roof) 0.278 (Internal) 0.285 (Ground Floor)

Time Now	Date	Program
12:35:32	24:Feb:02	A-Tas 8.31

DATABASE CONSTRUCTION

C-Code: **wall/1**	Construction name: **wall**

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.400	0.400	0.900	0.900	2.216	5.2

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1plast/11 PLASTER 1 *4	12.70	0.420	1200.0	837.0	-	11.000
2	am1brick/8 BRICK COMMON 1 *3	254.00	0.650	1530.0	920.0	-	9.600
3	am1plast/11 PLASTER 1 *4	12.70	0.420	1200.0	837.0	-	11.000

U VALUES (W/m2K): 1.604 (Wall) 1.673 (Roof) 1.460 (Internal) 1.686 (Ground Floor)

Time Now	Date	Program
22:07:05	23:Mar:02	A-Tas 8.31

DATABASE CONSTRUCTION

C-Code: **ceiling/5**	**Construction name: ceiling**

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.600	0.400	0.900	0.900	1.148	5.2

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	amlplast/11 PLASTER 1 *4	12.70	0.420	1200.0	837.0	-	11.000
2	amlconcl/1 CONCRETE 1:2:4 *3	127.00	1.400	2360.0	1030.0	-	34.000
3	amlplast/11 PLASTER 1 *4	12.70	0.420	1200.0	837.0	-	11.000
4	amlcav/26 500MM AIR (DOWNWARD FLOW)	500.00	-	-	-	0.050	1.000
5	amlins/18 PVC, EXPANDED *2	1.50	0.045	70.0	1000.0	-	40.000
6	amlins/14 POLYSTRENE, EXPANDED, CLOSED CELL *3	12.70	0.033	25.0	1200.0	-	192.000
7	amlins/18 PVC, EXPANDED *2	3.00	0.045	70.0	1000.0	-	40.000

U VALUES (W/m2K): 0.959 (Wall) 0.983 (Roof) 0.905 (Internal) 0.987 (Ground Floor)

Time Now	Date	Program
12:40:00	24:Feb:02	A-Tas 8.31

DATABASE CONSTRUCTION

C-Code: **glass/5**	Construction name: **window glass**

TRANSPARENT CONSTRUCTION External Blind? [No] Internal Blind? [No]

Solar Trans- mittance	External Solar Absorptance (ext. surf.)	(int. surf.)	Internal Solar Absorptance (int. surf.)	(ext. surf.)	Light Trans- mittance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)
0.780	0.075	0.075	0.075	0.075	0.870	0.845	0.845	166.667

Layer Number	M-Code & Material Name	Width (mm)	Solar Tran.	Ext. Solar Refl.	Int. Solar Refl.	Ext. Emis.	Int. Emis.	Conductivity (W/m C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1pilk/2 6MM CLEAR FLOAT	6.00	0.780	0.070	0.070	0.845	0.845	1.000	-	99999.000
2										

U VALUES (W/m2K): 5.445 (Wall) 6.386 (Roof) TOTAL SOLAR TRANSMITTANCE: 0.820 (Pilkington)

Time Now	Date	Program
12:41:21	24:Feb:02	A-Tas 8.31

DATABASE CONSTRUCTION

C-Code: intwall/1	Construction name: wall

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.400	0.400	0.900	0.900	3.908	1.7

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	am1plast/11 PLASTER 1 *4	12.70	0.420	1200.0	837.0	-	11.000
2	am1brick/8 BRICK COMMON 1 *3	127.00	0.650	1530.0	920.0	-	9.600
3	am1plast/11 PLASTER 1 *4	12.70	0.420	1200.0	837.0	-	11.000

U VALUES (W/m2K): 2.337 (Wall) 2.486 (Roof) 2.042 (Internal) 2.515 (Ground Floor)

Time Now	Date	Program
12:42:32	24:Feb:02	A-Tas 8.31

DATABASE CONSTRUCTION

C-Code: door/2	**Construction name:** door

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)	Time constant (hours)
0.600	0.600	0.900	0.900	4.105	0.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside 2	am1wood/20 MAHOGANY ACROSS GRAIN 10% m.c. *1	38.00	0.156	700.0	1420.0	-	11.420

U VALUES (W/m2K): 2.406 (Wall) 2.564 (Roof) 2.095 (Internal) 2.595 (Ground Floor)

Time Now	Date	Program
22:53:26	23:Mar:02	A-Tas 8.31

DATABASE CONSTRUCTION

C-Code: ceiling6/1	Construction name: ceiling

OPAQUE CONSTRUCTION

External Solar Absorptance	Internal Solar Absorptance	External Emissivity	Internal Emissivity	Conductance (W/m2 C)
0.400	0.400	0.900	0.900	6.614

Time constant (hours)
2.0

Layer Number	M-Code & Material Name	Width (mm)	Conductivity (W/m C)	Density (kg/m3)	Specific Heat (J/kg C)	Convection Coefficient (W/m2 C)	Vapour Diffusion Factor
Inside	amlplast/11 PLASTER 1 *4	12.70	0.420	1200.0	837.0	-	11.000
2	amlconcl/1 CONCRETE 1:2:4 *3	127.00	1.400	2360.0	1030.0	-	34.000
3	amlplast/11 PLASTER 1 *4	12.70	0.420	1200.0	837.0	-	11.000

U VALUES (W/m2K): 3.094 (Wall) 3.360 (Roof) 2.597 (Internal) 3.413 (Ground Floor)

e) Aperture Types

Building Name: T1Room   Building Data File: T1Room.bdf.01   Revision: 81
Time: 22:56:55   Date: 23:Mar:02   Program: A-Tas 8.31

Building Element	Window Height (m)	Window Width (m)	Window Area (m2)	Shel-tered?	Sched-ule	Openable Prop.	Aperture factor file name (for imported aperture factors)
5. w1	1.371	1.270	1.741	No	a	0.500	
7. hw	0.457	0.508	0.232	No	a	0.500	
9. w2	1.371	1.778	2.438	No	a	0.500	
10. d1	2.133	0.762	1.625	No	a	0.500	
11. w3	1.371	0.508	0.696	No	a	0.500	
12. w4	1.371	3.683	5.049	No	a	0.500	
13. w5	1.371	1.524	2.089	No	a	0.500	
14. w6	1.371	1.651	2.264	No	a	5.000	
15. d2	2.133	1.016	2.167	No	a	1.000	

f) Surface Geometry

Building Name: T1Room   Building Data File: T1Room.bdf.01   Revision: 81
Time: 23:01:44   Date: 23:Mar:02   Program: A-Tas 8.31

ZONE 6 Test Room

Internal Volume (m3)	Internal Floor Area (m2)	Relative Orientation (deg.)	Optional Fixed Convection Coefft. (W/m2 C)
41.2	14.9	0.0	

Surface No.	Building Feature	Orientation (deg.)	Slope (deg.)	Area (m2)	Shad. Feat. No.	Mean Altitude	Plan Hydr. Dia.	Aperture no.	Building Element
1	->Zone 1	Floor	180.0	16.38	0	2.92			-5. Ceiling /Upper Floor
2	Exposed	Ceiling	0.0	16.38	0	5.84			7. Ceiling
3	Transp.	90 (E)	90.0	2.44	2	4.37	0.00	13	13. w2
4	Exposed	90 (E)	90.0	7.68	0	4.38			4. External Wall
5	Exposed	45 (NE)	90.0	3.26	0	4.38			4. External Wall
6	Transp.	0 (N)	90.0	1.74	1	4.37	0.00	14	6. w1
7	Exposed	0 (N)	90.0	6.83	0	4.38			4. External Wall
8	->Zone 10	270 (W)	90.0	7.73	0	4.30			11. Internal Wall-1
9	->Zone 9	270 (W)	90.0	2.17	0	3.99	0.00	15	19. d2
10	->Zone 9	270 (W)	90.0	1.77	0	4.69			11. Internal Wall-1
11	->Zone 8	180 (S)	90.0	5.34	0	4.30			-3. Internal Wall
12	->Zone 7	180 (S)	90.0	0.70	3	4.37	0.00	-16	-15. w3
13	->Zone 7	180 (S)	90.0	1.63	0	3.99	0.00	-17	-14. d1
14	->Zone 7	180 (S)	90.0	2.14	0	4.52			-3. Internal Wall

g) Internal Conditions

Building Name: T1Room   Building Data File: T1Room.bdf.01   Revision: 81
Time: 23:45:28 Date: 23:Mar:02   Program: A-Tas 8.31

Zone	Day type	IC - Code	Internal Conditions Description
6. Test Room	W+S+S DAY	room / 1	Test Room

Temp. Upper Limit (deg C)	Temp. Lower Limit (deg C)	Prop'l Control (deg C)	On-off Control (deg C)	Humidity Upper Limit (*)	Humidity Lower Limit (*)	Plant Max. Outside Temp. (deg C)	Plant Off Outside Temp. (deg C)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Include solar in MRT (y/n)?
Yes

Operating Period	Time Plant On	Time Plant Off	Heating (kW)	Cooling (kW)
1				
2				
3				
4				

	Radiant Prop.	View Coeff't.
Heating	0.000	0.249
Cooling	0.000	0.519
Lights	0.480	0.490
Occupants	0.200	0.227
Equipment	0.100	0.372

Occupation Period	Occupation Duration (hrs)	Infiltr. Air (ach)	Ventil. Air (ach)	Lighting Gain (W/m2)	Occupancy Sensible Gain (W/m2)	Occupancy Latent Gain (W/m2)	Equipment Sensible Gain (W/m2)	Equipment Latent Gain (W/m2)
1	10	2.000	0.000	3.000	3.500	0.000	0.000	0.000
2	5	0.500	0.000	0.000	0.000	0.000	0.000	0.000
3	9	2.000	0.000	3.000	3.500	0.000	0.000	0.000

k) Output Specification

Building Name: **T1Room** Building Data File: T1Room.bdf.01 Revision: 67
Time: 13:07:02 Date: 24:Feb:02 Program: A-Tas 8.31

Zone:	1	2	3	4	5	6	7	8	9	10	11
Air Temperature	*	*	*	*	*	*	*	*	*	*	*
Mean Rad. Temp.	*	*	*	*	*	*	*	*	*	*	
Resultant Temp.	*	*	*	*	*	*	*	*	*	*	
Sensible Load	*	*	*	*	*	*	*	*	*	*	*
Heating Load											
Cooling Load											
Solar Gain	*	*	*	*	*	*	*	*	*	*	
Lighting Gain	*	*	*	*	*	*	*	*	*	*	
Occ. Sens. Gain	*	*	*	*	*	*	*	*	*	*	
Equ. Sens. Gain											
Inf./Vent. Gain											
Air Movemt. Gain											
Bldg. H.T. Gain	*	*	*	*	*	*	*	*	*	*	
Extl. Cond. Opaq.	*	*	*	*	*	*	*	*	*	*	
Extl. Cond. Glaz.	*	*	*	*	*	*	*	*	*	*	
Humidity Ratio	*	*	*	*	*	*	*	*	*	*	*
Rel. Humidity	*	*	*	*	*	*	*	*	*	*	
Occ. Latent Gain											
Equ. Latent Gain											
Latent Load											
Hum. Load											
Dehum. Load											
Ext. Surf. Temps											
Int. Surf. Temps											
Ext. Surf. Solar											
Int. Surf. Solar											

APPENDIX A 4 FIELD DATA

A 4.1 Climatic Data from Field Study (in deg C) for Test Room without Roof Insulation

Date	Time	Indoor	RH (%)	Outdoor	Rooftop	Globe	Ceiling
18-Jun-02	12:33 AM	29.9	89.8	27.91	29.5	29.9	28.31
	1:33 AM	29.5	89.8	27.52	29.1	29.9	28.31
	2:33 AM	29.5	91.7	27.52	28.7	29.5	28.31
	3:33 AM	29.1	91.7	27.52	28.7	29.5	28.31
	4:33 AM	29.1	91.7	27.52	28.7	29.5	27.91
	5:33 AM	29.1	91.7	27.52	28.31	29.1	27.91
	6:33 AM	29.1	93.8	28.31	28.7	29.1	27.91
	7:33 AM	29.1	93.8	29.9	29.1	29.1	28.31
	8:33 AM	29.1	93.8	30.31	29.5	29.5	28.7
	9:33 AM	29.9	89.8	31.12	29.9	29.9	29.9
	10:33 AM	29.9	88	31.93	35.27	30.31	31.12
	11:33 AM	30.71	82.6	33.17	39.22	30.71	31.93
	12:33 PM	31.12	78.5	33.59	41.05	31.52	33.59
	1:33 PM	31.52	79.4	34.43	43.42	32.34	34.43
	2:33 PM	31.93	76.8	34.01	43.42	32.76	36.13
	3:33 PM	32.34	77.6	33.59	41.99	33.17	37.44
	4:33 PM	32.76	75.2	33.59	41.05	33.17	37.88
	5:33 PM	32.76	77.5	31.93	38.77	33.17	37.88
	6:33 PM	32.76	78.4	31.12	37	32.76	37.44
	7:33 PM	32.76	79.3	30.31	35.27	32.34	36.13
	8:33 PM	32.34	81.4	29.9	34.01	32.34	34.85
	9:33 PM	31.93	81.4	29.5	32.76	31.93	34.01
	10:33 PM	31.52	82.5	29.1	31.93	31.52	32.76
	11:33 PM	31.93	82.5	29.1	30.71	31.52	31.93
19-Jun-02	12:33 AM	31.52	82.5	28.7	30.31	31.52	31.52
	1:33 AM	31.12	85	28.31	29.9	31.12	31.12
	2:33 AM	30.71	85.1	28.31	29.5	31.12	30.71
	3:33 AM	30.71	86.5	28.31	29.1	30.71	30.31
	4:33 AM	30.31	86.5	28.31	28.7	30.71	29.9
	5:33 AM	30.31	86.5	28.31	28.31	30.31	29.9
	6:33 AM	30.31	86.5	29.1	28.7	30.31	29.5
	7:33 AM	30.31	88	29.9	30.31	30.31	29.5
	8:33 AM	30.31	88	30.31	31.12	30.71	30.31
	9:33 AM	30.71	85.1	31.52	34.01	31.12	31.12
	10:33 AM	31.12	82.6	33.17	36.57	31.12	32.76
	11:33 AM	31.93	79.4	34.43	41.52	31.93	34.43
	12:33 PM	31.93	77.6	34.43	43.91	33.17	37.44
	1:33 PM	32.76	75.9	34.85	46.4	33.59	40.59
	2:33 PM	33.17	73.7	33.59	44.89	34.01	42.46
	3:33 PM	33.59	72.4	34.43	43.42	34.43	42.46
	4:33 PM	33.59	71.8	32.76	41.52	34.43	42.46
	5:33 PM	33.59	70.7	31.93	39.67	34.01	41.52
	6:33 PM	33.17	69.7	31.52	37.44	33.17	39.67
	7:33 PM	33.17	69.2	30.71	35.7	33.17	37.88
	8:33 PM	32.76	72.5	29.9	34.01	32.76	36.57
	9:33 PM	32.34	75.2	29.5	32.76	32.34	35.27
	10:33 PM	31.93	77.6	29.1	31.52	31.93	34.01
	11:33 PM	31.93	78.5	29.1	31.12	31.93	33.17
20-Jun-02	12:33 AM	31.93	79.4	28.7	30.31	31.93	32.34
	1:33 AM	31.52	80.4	28.31	29.9	31.52	31.93
	2:33 AM	31.12	80.4	28.31	29.5	31.52	31.12
	3:33 AM	31.12	81.5	28.31	29.1	31.12	30.71
	4:33 AM	31.12	81.5	28.31	28.7	31.12	30.71
	5:33 AM	30.71	82.6	28.31	28.7	31.12	30.31
	6:33 AM	30.71	82.6	29.1	29.1	31.12	29.9
	7:33 AM	30.71	83.8	30.31	30.31	30.71	29.9
	8:33 AM	30.71	81.5	31.12	31.93	31.12	30.71
	9:33 AM	31.12	81.5	30.71	32.76	31.12	31.93
	10:33 AM	31.12	79.5	33.17	35.7	31.52	32.76
	11:33 AM	31.52	77.6	32.34	37	31.93	34.01
	12:33 PM	31.52	80.4	31.12	34.43	32.34	35.27
	1:33 PM	31.93	76	31.52	37	32.34	35.27
	2:33 PM	32.34	78.4	34.85	37	32.34	35.27
	3:33 PM	32.34	76	34.85	35.7	32.34	35.27
	4:33 PM	32.76	76.7	34.85	37	32.76	35.27
	5:33 PM	32.34	74.5	31.93	35.7	32.34	34.85
	6:33 PM	32.34	73.2	30.31	34.01	32.34	34.01
	7:33 PM	31.93	71.5	29.5	32.34	31.52	32.76
	8:33 PM	31.52	74.6	29.1	31.52	31.12	31.12
	9:33 PM	31.52	76.8	29.1	30.71	31.12	30.31
	10:33 PM	31.12	78.5	28.7	29.9	30.71	29.9
	11:33 PM	31.12	79.5	28.7	29.5	31.12	29.5

A 4.2 Climatic Data from Field Study (in deg C) for Test Room with Operable Roof Insulation at 450 mm

Date	Time	Indoor	RH (%)	Outdoor	Rooftop	Globe	Ceiling
23-Apr-02	12:08 AM	27.91	78	25.17	25.95	27.91	25.56
	1:08 AM	27.91	77.2	25.56	25.56	27.91	25.17
	2:08 AM	27.91	76.5	25.17	25.56	27.52	25.17
	3:08 AM	27.52	77.2	24.79	25.56	27.52	25.17
	4:08 AM	27.52	77.3	24.4	25.17	27.12	25.17
	5:08 AM	27.12	78.9	24.4	25.17	27.12	24.79
	6:08 AM	27.12	78.9	24.4	24.79	27.12	24.79
	7:08 AM	27.52	76.5	25.56	25.17	27.12	24.79
	8:08 AM	27.12	77.3	26.73	25.17	27.12	24.79
	9:08 AM	27.52	78.1	28.31	25.56	27.52	25.17
	10:08 AM	27.91	76.5	29.5	25.95	27.91	25.56
	11:08 AM	27.91	70.9	31.12	26.34	28.31	25.95
	12:08 PM	28.7	72.5	31.93	27.52	29.1	26.73
	1:08 PM	29.1	71.3	32.76	28.31	29.5	27.12
	2:08 PM	29.5	64.8	32.76	28.7	29.9	27.91
	3:08 PM	29.5	69.2	34.01	29.5	29.9	28.31
	4:08 PM	29.9	69.7	32.76	29.9	30.31	28.31
	5:08 PM	29.9	69.6	31.93	29.9	30.31	28.31
	6:08 PM	29.9	70.1	30.71	30.31	30.31	28.7
	7:08 PM	30.31	69.1	29.9	29.9	30.31	28.7
	8:08 PM	29.9	70.1	29.5	29.9	30.31	28.31
	9:08 PM	29.9	69.1	29.1	29.5	30.31	28.31
	10:08 PM	29.9	66.2	28.7	29.1	29.9	28.31
	11:08 PM	29.9	67.8	28.7	28.7	29.9	28.31
24-Apr-02	12:08 AM	29.5	70.7	27.91	28.31	29.5	27.91
	1:08 AM	29.5	74.2	27.52	28.31	29.1	27.52
	2:08 AM	29.1	76.3	26.73	27.91	29.1	27.52
	3:08 AM	28.7	77.1	26.34	27.52	28.7	27.12
	4:08 AM	28.7	77.9	26.34	27.12	28.7	27.12
	5:08 AM	28.7	79.7	26.34	26.73	28.7	26.73
	6:08 AM	28.7	78.8	26.73	26.73	28.7	26.73
	7:08 AM	28.7	80.6	27.12	26.73	29.1	27.12
	8:08 AM	29.1	80.6	30.31	27.12	29.5	27.12
	9:08 AM	29.5	79.6	29.9	27.52	29.5	27.91
	10:08 AM	29.9	77	31.52	28.31	29.9	28.7
	11:08 AM	29.9	77	32.34	28.7	30.31	29.1
	12:08 PM	30.31	76.2	33.17	29.5	30.71	29.5
	1:08 PM	30.71	70.5	34.01	30.31	31.12	30.31
	2:08 PM	30.71	70.5	33.17	30.71	31.52	30.71
	3:08 PM	31.12	71.5	34.43	31.12	31.52	31.12
	4:08 PM	31.52	65.9	33.59	31.52	31.93	31.52
	5:08 PM	31.52	62.7	33.59	31.52	31.93	31.93
	6:08 PM	31.93	65.5	31.52	31.52	32.34	31.93
	7:08 PM	31.52	66.3	31.12	31.52	31.93	31.93
	8:08 PM	31.52	66.7	30.71	31.12	31.93	31.52
	9:08 PM	31.52	69.9	30.71	31.12	31.93	31.12
	10:08 PM	31.52	73.9	29.5	30.71	31.52	31.12
	11:08 PM	31.12	77.7	29.1	30.71	31.52	30.71
25-Apr-02	12:08 AM	31.12	76.1	28.31	30.31	31.12	30.71
	1:08 AM	31.12	76.9	27.91	29.9	31.12	30.31
	2:08 AM	30.71	76.1	27.52	29.5	30.71	29.9
	3:08 AM	30.31	60.3	25.95	29.1	30.31	29.5
	4:08 AM	30.31	64.3	24.4	28.7	30.31	29.1
	5:08 AM	29.9	65.8	24.4	27.91	29.9	28.31
	6:08 AM	29.9	65.5	24.01	27.52	29.5	27.91
	7:08 AM	29.5	66.6	25.56	27.52	29.5	27.52
	8:08 AM	29.9	67	28.7	27.52	29.9	27.91
	9:08 AM	29.9	69.2	29.5	27.91	30.31	28.31
	10:08 AM	30.31	69.7	30.71	28.31	30.31	29.1
	11:08 AM	30.31	66.9	32.76	29.1	30.71	29.5
	12:08 PM	30.71	68.5	33.17	29.9	31.12	30.31
	1:08 PM	31.12	64.8	34.01	30.71	31.52	31.12
	2:08 PM	31.52	62.3	34.43	31.12	32.34	31.52
	3:08 PM	31.93	62.3	34.43	31.93	32.34	31.93
	4:08 PM	32.34	62.8	34.85	32.34	32.76	32.34
	5:08 PM	32.34	67.4	34.43	32.34	32.76	32.76
	6:08 PM	32.34	68.3	31.93	32.34	32.76	32.76
	7:08 PM	32.34	70.3	31.12	32.34	32.76	32.76
	8:08 PM	31.93	72	30.71	31.93	32.34	32.34
	9:08 PM	31.93	73.2	29.9	31.52	31.93	31.93
	10:08 PM	31.93	76.1	29.5	31.12	31.93	31.52
	11:08 PM	31.52	76.9	29.1	31.12	31.52	31.12

A 4.3 Climatic Data from Field Study (in deg C) for Test Room with Operable Roof Insulation at 300 mm

Date	Time	Indoor	RH (%)	Outdoor	Rooftop	Globe	Ceiling
12-May-02	12:17 AM	27.52	78.9	23.24	25.17	27.52	25.95
	1:17 AM	27.12	82.8	24.4	24.79	27.12	25.56
	2:17 AM	27.12	84	24.4	24.79	27.12	25.56
	3:17 AM	27.12	86.6	24.4	24.79	26.73	25.17
	4:17 AM	26.73	88.2	24.79	24.79	26.73	25.17
	5:17 AM	26.73	89.8	24.79	24.79	26.73	25.17
	6:17 AM	26.73	89.8	25.17	24.79	26.73	25.17
	7:17 AM	26.73	91.7	25.95	25.17	26.73	25.56
	8:17 AM	27.12	93.8	27.91	25.56	27.12	25.95
	9:17 AM	27.52	99.3	29.1	26.34	27.91	26.73
	10:17 AM	27.91	99.3	29.9	26.73	28.31	27.52
	11:17 AM	28.31	99.3	31.12	27.52	28.7	27.91
	12:17 PM	29.1	96.3	32.76	27.91	29.5	28.31
	1:17 PM	29.9	89.8	33.17	28.7	30.31	29.1
	2:17 PM	30.31	89.7	33.59	29.1	30.71	29.5
	3:17 PM	30.31	88	34.01	29.5	30.71	29.9
	4:17 PM	30.31	88	33.17	29.9	30.71	29.9
	5:17 PM	30.71	89.7	32.76	30.31	30.71	30.31
	6:17 PM	30.31	88	30.31	30.31	30.31	29.9
	7:17 PM	29.9	89.8	29.1	29.9	29.9	29.9
	8:17 PM	29.9	86.5	28.31	29.9	30.31	29.5
	9:17 PM	29.5	83.9	27.91	29.5	29.5	28.7
	10:17 PM	29.5	88.1	27.91	29.1	29.5	28.31
	11:17 PM	29.5	89.8	27.91	29.1	29.5	28.31
13-May-02	12:17 AM	29.1	89.8	27.91	28.7	29.5	28.31
	1:17 AM	29.1	91.7	27.91	28.7	29.5	28.31
	2:17 AM	29.1	91.7	27.52	28.31	29.1	27.91
	3:17 AM	29.1	91.7	27.52	28.31	29.1	27.91
	4:17 AM	29.1	91.7	27.52	27.91	29.1	27.91
	5:17 AM	29.1	91.7	27.52	27.91	29.1	27.91
	6:17 AM	28.7	91.7	27.52	27.91	29.1	27.91
	7:17 AM	29.1	93.8	27.91	27.91	29.1	27.91
	8:17 AM	29.1	93.8	30.31	28.31	29.1	28.31
	9:17 AM	29.5	91.7	31.12	28.7	29.9	28.7
	10:17 AM	29.9	89.8	31.93	29.1	30.31	29.1
	11:17 AM	30.31	88	32.76	29.9	30.71	29.5
	12:17 PM	30.71	85.1	33.17	30.31	30.71	29.5
	1:17 PM	31.12	81.5	34.01	30.71	31.93	29.9
	2:17 PM	31.52	76.8	34.43	31.12	31.93	30.31
	3:17 PM	31.52	77.6	35.7	31.52	31.52	30.31
	4:17 PM	31.52	76.1	34.43	31.93	31.93	30.71
	5:17 PM	31.52	75.3	33.59	31.93	31.52	30.31
	6:17 PM	31.12	72.7	31.12	31.93	31.52	30.31
	7:17 PM	31.12	77.7	30.31	31.52	31.12	29.9
	8:17 PM	31.12	79.5	29.9	31.12	31.12	29.5
	9:17 PM	31.12	80.4	29.5	31.12	31.12	29.1
	10:17 PM	30.71	81.5	29.1	30.71	31.12	29.1
	11:17 PM	30.71	82.6	28.7	30.31	30.71	29.1
14-May-02	12:17 AM	30.31	79.5	28.31	29.9	30.71	28.7
	1:17 AM	30.31	81.5	27.91	29.5	30.31	28.7
	2:17 AM	30.31	82.6	27.52	29.1	30.31	28.7
	3:17 AM	30.31	82.6	27.52	29.1	30.31	28.31
	4:17 AM	29.9	85.1	27.12	28.7	29.9	28.31
	5:17 AM	29.5	85.1	26.73	28.31	29.5	28.31
	6:17 AM	29.5	85.1	27.91	28.31	29.5	27.91
	7:17 AM	29.5	85.1	28.31	28.31	29.5	27.91
	8:17 AM	29.9	81.5	30.31	28.7	29.9	28.31
	9:17 AM	30.31	80.5	32.76	29.1	31.12	29.1
	10:17 AM	30.71	80.5	32.76	29.5	31.12	29.5
	11:17 AM	31.12	79.5	34.01	30.31	31.12	29.9
	12:17 PM	31.52	76.8	35.27	31.12	31.93	30.71
	1:17 PM	31.93	73.2	35.27	31.52	32.76	31.12
	2:17 PM	32.34	70.9	35.7	32.34	32.76	31.93
	3:17 PM	32.34	70.9	36.57	32.76	32.76	32.34
	4:17 PM	32.76	75.2	34.85	33.17	32.76	32.76
	5:17 PM	32.76	77.5	33.59	32.76	32.76	32.76
	6:17 PM	32.34	79.3	31.52	32.76	32.76	32.76
	7:17 PM	32.34	81.4	31.12	32.76	32.34	32.34
	8:17 PM	31.12	72.1	27.52	32.34	31.12	31.93
	9:17 PM	31.12	74.7	27.12	31.52	31.12	31.52
	10:17 PM	31.12	80.4	29.1	30.71	31.12	30.71
	11:17 PM	30.31	79.5	27.91	30.31	30.31	29.9

APPENDIX A 5 METEOROLOGICAL DATA OF DHAKA

Source: Bangladesh Meteorological Department, Agargaon, Dhaka

A 5.1 Monthly and Annual Ave. Maximum Temperature in Degree Celsius
Year: 1991-2000

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1991	24.3	28.9	32.5	33.9	31.8	31.5	32.1	31.8	30.6	31.0	28.3	24.7	30.1
1992	24.0	25.5	32.5	36.1	33.5	33.7	31.5	31.9	32.2	31.8	29.4	26.0	30.7
1993	24.5	28.8	30.9	33.0	31.6	31.7	31.4	30.9	31.5	31.5	29.5	27.1	30.2
1994	26.1	26.5	32.4	33.2	33.6	31.9	32.0	32.0	32.9	32.8	29.9	27.7	30.9
1995	25.4	28.0	33.8	36.5	34.6	32.8	31.8	32.5	32.4	32.8	29.8	26.3	31.4
1996	25.8	29.7	34.4	34.9	34.6	32.5	32.8	31.8	33.8	32.3	30.3	27.3	31.7
1997	25.1	27.8	33.1	31.1	33.7	33.3	31.7	32.7	31.5	32.1	30.4	25.0	30.6
1998	22.8	28.4	30.7	32.7	33.4	34.3	31.7	31.8	32.5	33.1	30.7	28.1	30.8
1999	26.9	31.2	34.8	36.0	32.8	32.5	31.5	31.7	31.6	31.8	30.4	27.1	31.5
2000	24.6	25.5	30.9	32.8	32.3	32.5	31.8	32.1	32.0	31.1	29.6	26.4	30.1
Mean	**25.0**	**28.0**	**32.6**	**34.0**	**33.2**	**32.7**	**31.8**	**31.9**	**32.1**	**32.0**	**29.8**	**26.6**	**30.8**

A 5.2 Monthly and Annual Ave. Minimum Temperature in Degree Celsius
Year: 1991-2000

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1991	13.8	17.5	21.9	24.4	23.3	25.9	26.7	26.4	25.7	24.5	19.0	15.0	22.0
1992	13.5	16.0	22.1	25.0	24.2	26.5	25.9	26.4	26.1	23.8	18.6	12.4	21.7
1993	12.0	16.7	18.1	22.7	23.5	25.7	26.2	26.4	25.6	23.8	19.2	13.7	21.2
1994	13.1	14.1	21.0	22.8	25.3	26.4	26.7	26.4	25.8	23.3	18.8	12.5	21.4
1995	11.3	15.7	19.3	24.6	26.3	26.9	26.3	26.5	26.3	24.0	19.9	13.3	21.7
1996	12.1	15.2	22.2	24.0	25.7	25.4	26.7	26.2	26.2	22.9	18.2	14.0	21.6
1997	11.5	14.5	21.1	21.1	24.6	25.8	26.4	26.6	25.5	22.2	18.9	14.5	21.0
1998	12.7	16.1	18.3	22.9	25.3	28.1	26.4	26.8	26.3	25.4	20.6	14.8	22.0
1999	12.7	16.5	21.0	26.0	25.1	26.5	26.2	26.4	25.9	24.5	19.0	14.9	22.1
2000	14.0	16.2	20.7	23.5	24.1	25.5	26.5	26.4	25.8	24.4	20.2	15.1	21.9
Mean	**12.7**	**15.9**	**20.6**	**23.7**	**24.7**	**26.3**	**26.4**	**26.5**	**25.9**	**23.9**	**19.2**	**14.0**	**21.7**

A 5.3 Monthly and Annual Ave. Maximum Temperature in Degree Celsius
Year: 1981-1990

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1981	25.1	26.9	30.4	30.6	31.9	32.7	30.5	32.4	31.7	32.3	30.0	25.5	30.0
1982	26.3	27.3	30.8	32.8	34.6	31.6	32.0	30.9	32.1	32.0	28.0	25.6	30.3
1983	24.5	26.7	31.4	32.9	32.3	32.9	31.9	31.1	31.1	30.6	30.3	25.9	30.1
1984	24.9	27.6	34.5	34.4	31.4	30.9	30.9	31.3	31.4	31.9	29.8	26.8	30.5
1985	26.2	29.2	34.0	33.6	32.3	31.7	30.7	31.8	31.8	32.5	30.2	28.0	31.0
1986	26.5	29.4	35.0	33.4	33.8	33.4	31.9	33.0	31.2	31.4	29.5	27.1	31.3
1987	26.7	30.4	33.1	33.8	34.9	33.7	31.3	31.9	32.2	32.4	30.2	27.3	31.5
1988	27.2	30.1	32.6	35.3	33.1	32.0	32.2	31.8	33.0	32.7	30.5	27.4	31.5
1989	25.4	28.8	33.8	36.1	34.4	32.9	32.1	32.9	32.0	31.5	30.2	26.6	31.4
1990	25.5	27.5	28.8	31.9	32.7	32.3	31.1	32.1	32.0	30.2	29.8	26.5	30.0
Mean	**25.8**	**28.4**	**32.4**	**33.5**	33.1	**32.4**	**31.5**	**31.9**	**31.9**	31.8	**29.9**	**26.7**	**30.8**

A 5.4 Monthly and Annual Ave. Minimum Temperature in Degree Celsius
Year: 1981-1990

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1981	13.3	15.4	19.8	21.9	23.6	26.4	26.0	26.4	26.1	23.5	18.1	13.6	21.2
1982	12.2	15.0	19.1	22.5	25.0	25.9	26.8	26.1	25.9	23.3	17.9	13.7	21.1
1983	12.6	14.4	20.6	22.6	24.4	26.1	26.9	26.2	26.2	23.8	19.4	14.1	21.4
1984	13.1	15.0	21.0	24.5	24.4	25.8	26.0	26.2	25.4	25.6	18.5	14.7	21.7
1985	14.5	16.1	22.7	24.6	24.1	26.1	25.9	26.6	25.9	23.9	18.9	15.3	22.0
1986	13.9	16.3	20.7	22.7	23.8	26.6	26.1	26.6	25.2	23.2	19.8	15.2	21.7
1987	13.1	16.4	20.7	23.9	24.6	27.2	26.4	26.5	26.5	24.3	20.1	15.2	22.1
1988	13.6	16.3	20.7	24.4	24.8	25.7	26.6	26.9	26.7	23.8	19.6	18.0	22.1
1989	11.3	15.4	20.3	25.0	25.9	26.3	26.3	26.9	26.1	24.5	18.8	13.3	21.7
1990	14.3	17.3	19.7	22.7	25.0	26.7	26.0	26.9	26.3	23.6	21.5	16.0	22.2
Mean	**13.2**	**15.8**	**20.5**	**23.5**	**24.6**	**26.3**	**26.3**	**26.5**	**26.0**	**24.0**	**19.3**	**14.7**	**21.7**

A 5.5 Monthly and Annual Ave. Relative Humidity in Percent
Year: 1991-2000

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1991	71.0	66.0	66.0	71.0	85.0	86.0	84.0	84.0	89.0	83.0	72.0	76.0	78.0
1992	76.0	71.0	63.0	69.0	76.0	80.0	84.0	82.0	80.0	79.0	74.0	75.0	76.0
1993	73.0	69.0	62.0	70.0	80.0	83.0	85.0	85.0	84.0	82.0	79.0	75.0	77.0
1994	73.0	69.0	68.0	71.0	77.0	83.0	80.0	82.0	79.0	77.0	75.0	72.0	76.0
1995	67.0	70.0	58.0	66.0	76.0	82.0	84.0	83.0	84.0	81.0	79.0	77.0	76.0
1996	73.0	67.0	67.0	70.0	78.0	83.0	84.0	85.0	83.0	80.0	76.0	72.0	77.0
1997	70.0	64.0	67.0	75.0	77.0	82.0	86.0	84.0	86.0	78.0	75.0	80.0	77.0
1998	77.0	68.0	64.0	75.0	78.0	81.0	87.0	86.0	85.0	82.0	78.0	77.0	78.0
1999	72.0	65.0	58.0	69.0	79.0	83.0	86.0	84.0	84.0	83.0	76.0	71.0	76.0
2000	72.0	61.0	63.0	73.0	78.0	80.0	80.0	81.0	81.0	82.0	73.0	69.0	74.0
Mean	**72.4**	**67.0**	**63.6**	**70.9**	**78.4**	**82.3**	**84.0**	**83.6**	**83.5**	**80.7**	**75.7**	**74.4**	**76.5**

A 5.6 Monthly and Annual Ave. Relative Humidity in Percent
Year: 1981-1990

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1981	71.0	68.0	66.0	77.0	79.0	81.0	89.0	84.0	84.0	71.0	67.0	72.0	76.0
1982	69.0	63.0	64.0	73.0	74.0	86.0	85.0	86.0	84.0	78.0	76.0	74.0	76.0
1983	73.0	64.0	70.0	73.0	80.0	85.0	85.0	87.0	88.0	85.0	70.0	73.0	78.0
1984	69.0	62.0	57.0	71.0	84.0	86.0	87.0	86.0	83.0	79.0	69.0	72.0	75.0
1985	71.0	60.0	70.0	75.0	79.0	85.0	86.0	84.0	84.0	75.0	71.0	71.0	76.0
1986	72.0	59.0	56.0	75.0	76.0	83.0	85.0	83.0	86.0	81.0	79.0	76.0	76.0
1987	73.0	65.0	66.0	75.0	75.0	83.0	89.0	85.0	84.0	78.0	74.0	76.0	77.0
1988	72.0	68.0	69.0	74.0	81.0	85.0	85.0	85.0	82.0	78.0	75.0	79.0	78.0
1989	69.0	64.0	59.0	68.0	79.0	82.0	85.0	80.0	86.0	82.0	74.0	73.0	75.0
1990	78.0	70.0	73.0	77.0	80.0	84.0	88.0	83.0	85.0	79.0	76.0	72.0	79.0
Mean	**71.7**	**64.3**	**65.0**	**73.8**	**78.7**	**84.0**	**86.4**	**84.3**	**84.6**	**78.6**	**73.1**	**73.8**	**76.6**

A 5.7 Monthly and Annual Rainfall in Millimeter
Year: 1991-2000

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1991	27.0	8.0	46.0	53.0	529.0	320.0	318.0	345.0	692.0	392.0	14.0	106.0	2850.0
1992	1.0	47.0	0.0	25.0	153.0	132.0	386.0	182.0	158.0	83.0	2.0	0.0	1169.0
1993	0.0	52.0	88.0	113.0	556.0	504.0	421.0	432.0	417.0	217.0	19.0	0.0	2819.0
1994	13.0	54.0	115.0	201.0	254.0	266.0	153.0	246.0	169.0	55.0	14.0	0.0	1540.0
1995	8.0	31.0	0.0	88.0	264.0	237.0	354.0	360.0	205.0	91.0	112.0	1.0	1751.0
1996	0.0	21.0	54.0	199.0	208.0	343.0	257.0	361.0	244.0	357.0	0.0	0.0	2044.0
1997	2.0	7.0	136.0	133.0	151.0	249.0	549.0	230.0	440.0	30.0	1.0	22.0	1950.0
1998	49.0	4.0	83.0	178.0	405.0	91.0	521.0	552.0	26.0	100.0	83.0	0.0	2312.0
1999	0.0	0.0	0.0	21.0	428.0	348.0	553.0	282.0	361.0	368.0	13.0	0.0	2374.0
2000	13.0	44.0	172.0	189.0	471.0	183.0	200.0	363.0	214.0	272.0	0.0	0.0	2121.0
Mean	**11**	**27**	**69**	**120**	**342**	**267**	**371**	**335**	**293**	**197**	**26**	**13**	**2093**

A 5.8 Monthly and Annual Rainfall in Millimeter
Year: 1981-1990

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1981	10.0	42.0	109.0	274.0	272.0	168.0	356.0	188.0	320.0	82.0	9.0	35.0	1865.0
1982	0.0	15.0	81.0	104.0	154.0	514.0	136.0	346.0	258.0	146.0	51.0	0.0	1805.0
1983	7.0	61.0	138.0	318.0	348.0	300.0	179.0	437.0	322.0	253.0	25.0	18.0	2414.0
1984	13.0	1.0	5.0	124.0	707.0	637.0	694.0	311.0	478.0	58.0	0.0	0.0	3023.0
1985	8.0	1.0	195.0	176.0	300.0	399.0	262.0	317.0	306.0	79.0	0.0	10.0	2053.0
1986	22.0	0.0	23.0	247.0	191.0	304.0	443.0	171.0	687.0	237.0	172.0	3.0	2500.0
1987	4.0	0.0	33.0	230.0	109.0	316.0	526.0	462.0	363.0	104.0	7.0	33.0	2187.0
1988	0.0	44.0	74.0	282.0	513.0	580.0	255.0	169.0	196.0	213.0	153.0	3.0	2482.0
1989	0.0	32.0	0.0	85.0	228.0	319.0	347.0	59.0	305.0	240.0	0.0	12.0	1627.0
1990	0.0	36.0	151.0	154.0	202.0	29.0	567.0	227.0	247.0	181.0	103.0	6.0	2103.0
Mean	**6**	**23**	**81**	**199**	**302**	**357**	**377**	**269**	**348**	**159**	**52**	**12**	**2206**

A 5.9 Bright Sun Shine Hour
Year: 1987-2001

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2001	7.94	7.19	8.75	8.55	6.07	3.85	4.55	5.08	4.65	5.60	6.19	7.19	6.30
2000	6.14	5.99	8.52	8.49	5.20	4.56	5.03	4.78	4.55	5.75	7.99	8.18	6.26
1999	7.21	7.47	8.28	8.36	5.49	4.97	3.85	3.85	3.54	5.24	8.02	7.39	6.14
1998	4.14	6.11	8.14	7.32	5.79	6.84	2.81	3.66	4.30	5.81	7.15	9.10	5.93
1997	5.19	7.45	7.74	7.34	7.64	5.57	4.13	4.84	4.60	8.48	6.04	5.62	6.22
1996	7.24	9.54	8.77	8.72	7.48	4.50	3.73	3.58	5.40	7.82	8.30	6.55	6.80
1995	7.16	6.21	7.73	8.49	6.62	4.74	4.01	4.37	3.86	6.85	6.61	6.87	6.13
1994	6.92	7.60	7.33	7.38	7.21	4.51	5.08	5.37	6.18	7.08	6.14	7.30	6.51
1993	6.30	7.40	7.80	7.80	6.20	5.50	4.10	3.60	4.70	5.80	7.40	7.50	6.18
1992	6.34	6.88	7.02	7.74	7.14	6.08	4.01	4.80	5.66	6.40	7.20	7.00	6.36
1991	6.60	7.90	7.7	7.03	3.74	3.16	3.99	4.92	2.72	5.42	7.41	5.76	5.53
1990	7.50	8.40	6.2	7.30	6.50	4.50	3.90	5.00	4.80	6.40	7.30	7.30	6.26
1989	8.40	8.90	8.4	8.40	6.90	5.90	4.70	6.90	4.10	6.10	8.80	7.10	7.05
1988	8.10	8.10	8.2	7.60	6.70	3.80	4.50	3.90	6.10	8.30	7.70	7.40	6.70
1987	8.50	8.80	8.3	7.50	9.10	5.90	3.10	4.90	5.50	8.30	7.60	8.30	7.15
Mean	**6.91**	**7.60**	**7.93**	**7.87**	**6.52**	**4.96**	**4.10**	**4.64**	**4.71**	**6.62**	**7.32**	**7.24**	**6.37**

A 5.10 Monthly Prevailing Wind speed and in meter/second and Direction
Year: 1981-1990

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
	1981	1.4	1.8	2.6	2.5	2.2	2.0	2.1	1.4	1.9	1.8	1.5	1.4	1.88
	1982	1.4	1.7	1.4	3.2	3.0	2.5	2.4	2.5	2.1	1.1	1.2	1.5	2.00
	1983	1.7	2.7	3.1	2.6	1.9	2.4	2.4	2.5	2.2	2.0	1.5	1.9	2.24
	1984	1.2	1.7	2.1	2.9	2.2	2.6	2.1	2.4	1.9	1.8	1.3	2.0	2.01
	1985	1.3	2.1	2.5	2.4	2.2	2.1	1.8	2.6	1.7	3.5	1.5	1.6	2.10
	1986	1.2	1.5	2.4	3.0	1.8	1.7	2.2	2.0	2.9	1.3	1.0	1.5	1.89
	1987	1.6	1.7	2.3	2.7	2.5	2.3	2.2	2.1	1.9	1.7	1.4	1.2	1.96
	1988	1.3	1.5	2.5	2.7	3.2	2.2	2.3	2.3	2.0	1.9	1.2	1.4	2.03
	1989	1.8	2.3	1.8	3.3	3.1	2.5	2.2	1.9	2.2	1.9	1.3	1.5	2.15
	1990	1.3	1.8	3.2	3.3	2.0	2.5	2.3	2.2	2.4	3.9	1.3	1.5	2.31
	Mean	**1.4**	**1.9**	**2.4**	**2.9**	**2.4**	**2.3**	**2.2**	**2.2**	**2.1**	**2.1**	**1.3**	**1.6**	2.06
Direction		NW	N	SW	SW	S	SE	SE	SE	SE	N	NW	NW	