EXPERIMENTAL DETERMINATION OF COMFORT BENEFITS FROM COOL-ROOF APPLICATION TO AN UN-CONDITIONED BUILDING IN INDIA

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1. Abstract

Increasing roof reflectance reduces absorption of solar radiation, roof surface temperatures, and heat flux in the building interior. At the building level this leads to savings in air-conditioning energy consumption and increase in indoor comfort. At the macro level it helps in mitigating Urban Heat Island effect and reduces net solar radiation absorbed by the earth, lowering local air temperature and pollutant formation, and reducing global warming. Various studies have demonstrated energy savings in buildings using cool roofs. However, there are not many studies on the indoor comfort benefits of cool roofs for unconditioned interior spaces, especially in India. A study was performed on an un-conditioned, institutional building in a composite climate in India. Monitoring was performed for a period of six months (Jan – Jun, 2012) on two adjacent sections of continuous concrete roof surface, one of which had been previously coated with a white paint coating. The measured shortwave band-averaged (0.3-3 micron) solar reflectance was 0.28 and 0.57, for the uncoated and coated surfaces, respectively. The increased reflectivity reduced the seasonal average indoor air temperature and heat flux by 1.07^{o}C, and 14.4 W m^{-2}, respectively, with peak reductions of 1.38^{o}C and 18.3 Wm^{-2} in April, 2012. This increased the number of adaptive comfort hours by 80 hours (about 8%), providing a significant improvement in human comfort.

Keywords: Cool Roofs, Institutional Building, Un-conditional Building, Comfort Improvement, Air temperature

2. Introduction

A roof that reflects and emits the solar radiation back to the sky rather than transferring it into the building is termed as cool roof [1]. Cool roof helps in reducing air conditioning energy consumption in a conditioned building and improves thermal comfort in an un-conditioned building. The energy savings achieved in a building from cool roofs is dependent on various parameters like the location, orientation of the building, local shading by trees or other buildings, construction type, insulation type, plenum ventilation, equipment load, occupancy and operational schedules [2]. Thermal comfort benefits using cool roofs depend on other external parameters such as the location, orientation, ventilation rate, window size and type and the thermal comfort in a particular location tends to be adaptive in nature. The benefits of cool roof are summarized below.

2.1 Benefits of cool roofs:

Cools roofs have various benefits associated with them. This includes reducing heat island effect, negative radiative forcing of carbon di oxide in macro level and reducing the energy consumption of the building, increasing the comfort for the building occupants. Since our project is in building level we will look into the energy and comfort benefits of cool roofs in this section.

2.1.1 Energy savings from cool roofs:

It is notable that the maximum benefits of high albedo roofs can be seen in the hot and humid climatic zone. In one of the early experiments conducted by Florida solar energy center [3] to measure the benefits of cool roofs, an annual savings of 13,000 kWh was observed in the chiller energy consumption over 2 years period. The reduction in peak energy consumption (from 9 AM to 4 PM) was observed to by 1.5 kW (15% of the total demand) and the summer time peak reduction of 5.6 kW (35% of summer peak consumption) was observed. In an attempt to study to the impact of cool roofs on residential buildings [4], six houses were monitored in Florida. The cooling energy reduction ranged from 3% to 23%.

Researchers from Lawrence Berkeley National Laboratory conducted a series of experiments in California to quantify the benefits of high albedo roof. In a study to identify the savings from various Heat Island Effect mitigation strategies in three different climates (Baton Range, Salt Lake City and Sacramento), it was observed that the maximum savings from cool roofs occur in Hot and Dry climate [5]. A similar study [in Texas, in the city of Austin, on a retail store, showed a peak outside surface temperature reduction of 42^{o}F (from 168^{o}F in black roof to 126^{o}F in a white roof). For a building which has a roof area of 10000 ft^2, an energy savings of 3.6 Wh/ft^2 (11% of total cooling energy) in cooling energy and demand reduction of 0.35 Wh/ft^2 was observed.. In terms of percentage the average summer time energy saving observed is 11% of the total cooling energy. Usage of cool roofs also reduced the insulation requirement in the building. The payback that was observed in this study was almost instantaneous [6].

In Indian context cool roofs have been demonstrated to have energy savings of 20 – 22 kWh/m^2 of roof area, corresponding to an air conditioning energy use reduction of 14 – 26% in commercial buildings by changing the previously black roofs to white roofs. This study also estimated an annual savings of 13 – 14 kWh/ m^2 of roof area by applying a white coating to concrete roof, corresponding to an energy savings of 10 – 19% in the metropolitan of Hyderabad [7].

2.1.2 Comfort improvements from cool roofs

An investigation in the city of Poitiers, France on an un-conditioned building showed a tremendous increase in the thermal comfort of the building using cool roofs [8]. Experiments were performed for both insulated and non-insulated buildings. The cool roof installed on the test building had a solar reflectivity of 0.88 and a thermal emittance of 0.9. Operative temperature was used as a parameter to estimate the comfort of the building. In case of non-insulated roof, a reduction in the operative temperature of 9.9 ^{o}C (from 32.3 ^{o}C to 23.4 ^{o}C) in the attic and a reduction of 5.8 ^{o}C (from 29.4^{o}C to 23.6 ^{o}C) in the indoor room temperature were observed before and after installation of cool roofs. In case of insulated roof not much difference in the operative temperatures were observed. The gain observed is a maximum of 1^{o}C (from 30.2 ^{o}C to 29.3 ^{o}C) before and after installation of cool roof.

Another study was conducted to find the impact of cool roofs and green roofs in Mediterranean climate [9]. Cities from the northern (Barcelona), southern rim (Cairo) and from the middle basins

(Palermo) of the Mediterranean area were evaluated. The indoor thermal comfort was quantified as the number of hours in which temperatures exceeded a desirable operative temperature for the room. Three different set points were chosen for this study. In Barcelona the number of unmet hours above 26^{o}C has been reduced by 46% and 26% for non-insulated and insulated roofs. Metallic roof reduces the unmet hours by 20% in both cases. No unmet hours were witnessed above 28^{o}C in case of both cool and green roofs and the un-comfort hours have been reduced by 73% in metallic roofs. Despite the energy penalties seen in Barcelona from cool roofs due the increase in the thermal comfort of the building, cool roofs may still be considered for application.

A study in London on an office space performed a parametric analysis in which the roof albedo was varied from 0.1 to 1.0 [10]. When a cool roof is applied over a building with higher ventilation rate with a higher set point is we get more energy savings. The un-comfort hours for operative temperature and air temperature were plotted for different albedo values and the internal air temperature become to dip steeper after an albedo value of 0.6.

Most of the comfort related studies have been performed over residential buildings. In our study the comfort benefits of cool-roofs for an un-conditioned institutional building in warm climate of India has been examined. This represents an important real-world evaluation of an energy-efficient retrofit that serves as part of integrated design for sustainable urban environments.

3. Methodology

3.1 Monitoring site

To find the temperature and heat flux reductions institutional building has been chosen in composite climate zone in India. The building is located in Pantnagar, Uttarkand. (28.97°N, 79.41°E). There are major agricultural industrial activities happening in Pantnagar. This leads to higher aerosol levels in the site. Due to this the soiling of the roof surfaces was expected. Temperature sensors were installed both on the inside and outside surfaces. Apart from these heat flux coming inside the building and the inside air temperature were monitored.

At Pantnagar, the College of Biological and Physical Sciences was selected as a site for the roof monitoring project as shown in **Error! Reference source not found.**.and **Error! Reference**

source not found.. The buildings that are monitored are unconditioned. The building is an educational institute with two storey structure and has grey cemented flat roof. Roof of the building was retained grey cemented and other was painted with a white coating in May, 2011. The height of the floor is 3.65m with 100cm thick concrete roof. This building has research lab, library, discussion rooms, toilets etc. The roofs were located at the east side of the building as shown in Figure 2, where "dark" denotes sensor positions for uncoated roof, and "Cool" indicates sensor positions for cool roof.

It is interesting to note that the room which had the cool coating applied on it, has two of its walls exposed to the outside atmosphere. Both walls contained windows and operation of these windows might change the infiltration rates and heat gain from the walls when compared to the dark roof.

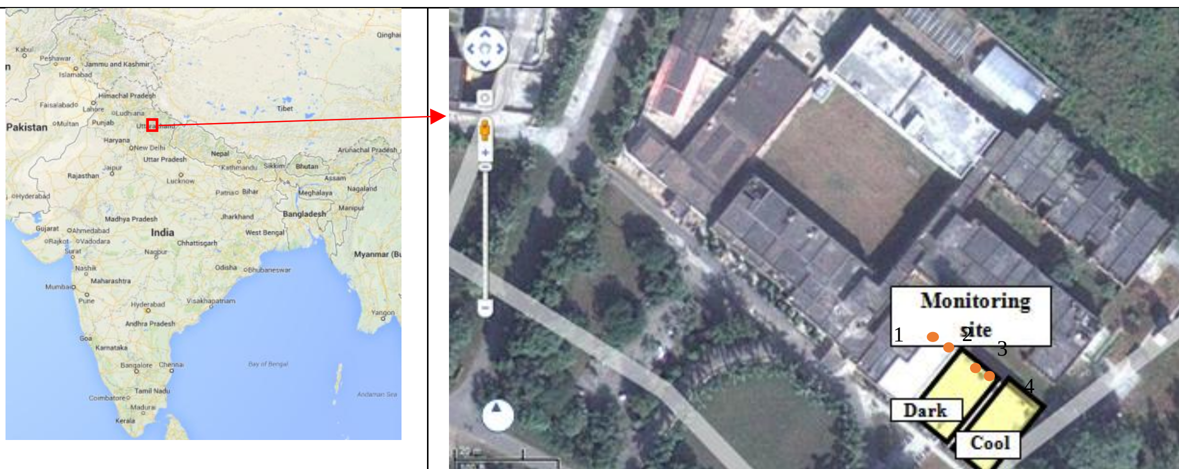


Figure 1: Satellite image of Pantnagar site: Block B Environmental Science Wing

3.2 Adaptive thermal comfort

Thermal comfort is expressed as a factor of outdoor effective temperature in various standards like ASHRAE, RP-884. This has been widely accepted method for evaluating the thermal comfort. To find the adaptive comfort, experimental data from over 22,346 building have been analyzed and it is found that indoor comfort temperatures are dependent on mean outdoor temperatures [11]. In another similar study thermal comfort can be expressed in terms of periods falling outside the desired band of adaptive temperature following the approach of Auliciems [12].

In an experiment performed to find the adaptive comfort temperatures in India, the neutral temperature, T_n [13], where found to be bound by the following relation.

$$T_n = 0.31 * T_{outside\ dry\ bulb} + 17.6^0 C \qquad \text{Eq (1)}$$

$$Comfort\ Band = T_n \pm 3.5^0 C$$

3.3 Roof Reflectance Measurements

Roof reflectance was measured as in support of a study of the radiative benefit of cool roofs [14]. Briefly, the shortwave reflectance was measured for the uncoated and cool roof as the ratio of up-welling to down-welling hemispheric shortwave (0.3-2 micron) radiation observed with a four-component radiometer (Kipp and Zonnen NR01) located in the middle of each roof segment. The average shortwave daytime surface reflectance of the roofs for the period from January through March, 2012 was 0.28 and 0.57 for dark roof and cool roof respectively.

3.4 Monitoring Equipment

Central data acquisition equipment was installed in the site. The measured parameters include outdoor air temperature, outdoor surface temperature, indoor surface temperature, and indoor air temperature and heat flux through the roof. The sensors used in the experiment are summarized below:

S.No	Equipment type	Equipment name
1	Data acquisition	Campbell Scientific - CR 1000
2	Heat Flux	Geothermal Heat flux sensors (ITI, GHT-2C)
3	Surface temperatures	(GG-T-30 Omega)
4	Indoor temperature	Omega: GG-T-30

Using these equipment monitoring was done for the indoor surface temperatures, outdoor surface temperatures, indoor air temperatures and heat flux for both dark roof and cool roof, through December 2011 to July 2012.

4. Results

From the collected data, over deck temperature, under deck temperature, indoor air temperature and heat flux were analyzed for the months of January through June. The data collected over 5 minutes interval was checked for its boundary values, rate of change in an interval of 5 minutes. The filtered data was averaged out to 30 minutes interval. A maximum reduction in the over deck temperature of 14.29^0C and an average reduction of 4.06^0C was observed between cool roof and dark roof. The mean reduction during operational hours (8 AM to 6 PM) for the entire period from Jan – Jun was found to be 7.74^0C. The maximum reduction in the over deck temperature was observed in the moths of April with a day time mean reduction of 9.29^0C and a 24 hours mean reduction of 4.94^0C.

In case of the under deck temperatures similar patterns have been observed compared to that of the over deck temperatures. From January through June over a period of 24 hours the mean reduction in the under deck temperature of 2.09^oC is observed and a daytime reduction of 1.97^oC were observed. The peak reduction happens in the month of June where a reduction of 6.7^oC is observed on 24 hours basis.

A mean heat flux reduction over 24 hours for the period of Jan – Jun was found to 14.41 W/m^2 and the daytime operational hours mean reduction was found to be 21.43 W/m^2. The maximum reduction in was observed in the month of April with a 24 hours mean of 18.31 W/m^2 and a day time reduction of 26.31 W/m^2. The shift in the number of hours with higher heat fluxes from dark roof to cool roof suggest the heat entering the building is lesser in case of cool roofs. This effect might be higher since there was also heat ingress from the windows and the walls which are exposed to the outside atmosphere.

These results demonstrate that the cool roof reduces heat flux and temperatures relative to the uncoated roof. Further the scatter plots for over deck temperature for white roof vs dark roof has a slope of 0.79, which implies that the over deck temperature of cool roof increases less quickly than the over deck temperature of dark roof. Similar plots for under deck temperature shows that the building with cool roof has lower under deck temperature than the building which has dark roof.

The difference between the under deck temperature and the indoor air temperature is directly proportional to the heat flux coming inside the building. Scatter plots of ΔT and the heat flux coming inside the building for both cool roof and dark roof has similar slope, which indicate the thermal mass of the roof are of similar nature.

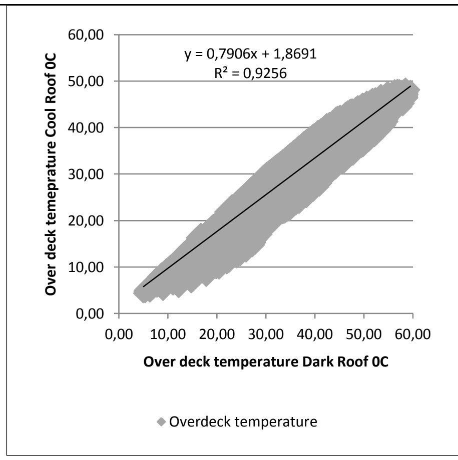


Figure 2: Over deck temperature cool roof vs. dark roofs

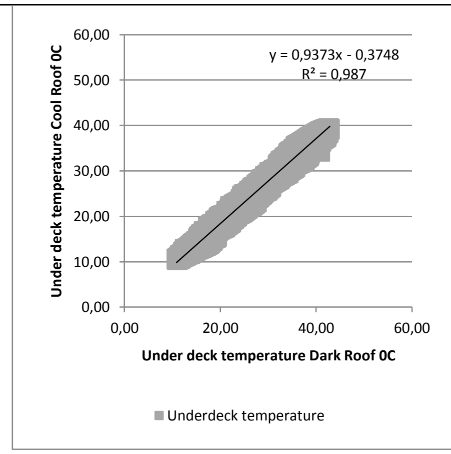


Figure 3: Under deck temperature cool roof vs. dark roof

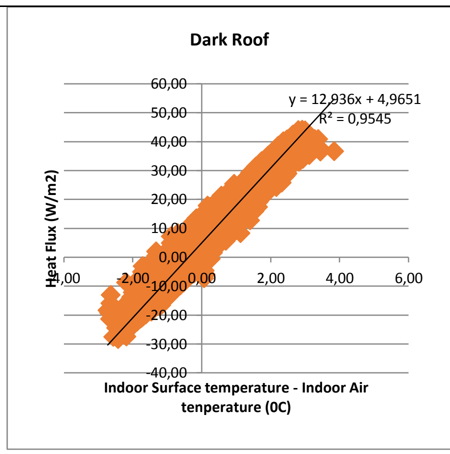


Figure 4: Heat flux vs. Delta T (Indoor surface temp - Indoor Air temp) - Dark Roof

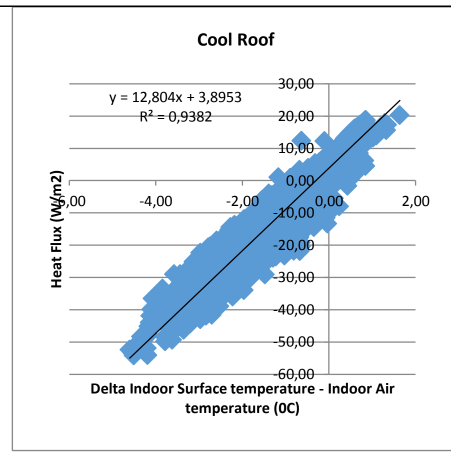


Figure 5: Heat flux vs. Delta T (Indoor surface temp - Indoor Air temp) - Cool Roof

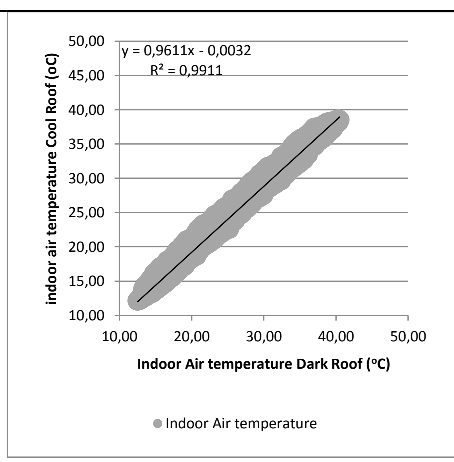


Figure 6: Indoor Air temperature Cool Roof vs Dark Roof

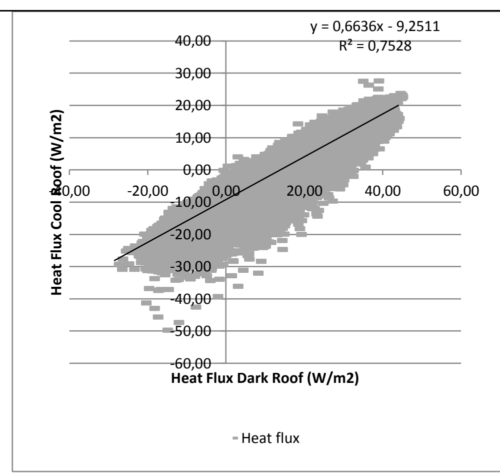


Figure 7: Heat Flux Cool Roof vs. Dark Roof

The mean reduction in the indoor air temperature in case of cool roof and dark roof was observed to 1.06^{0}C over a period of 24 hours and 0.44^{0}C over the operational hours of the building for the entire duration of analysis. This shows that the benefits from cool roof are higher in the night time than in the day. The maximum reduction in the mean indoor air temperature during day time happens in the month of June (0.89^{0}C) while the maximum reduction for 24 hours happens in the month of April (1.38^{0}C). The scatter plots between cool roof and dark roof for indoor air temperature (Figure 10) has a slope of 0.96 which implies that cool roof has lesser indoor air temperature than dark roof.

The heat flux entering the building is lower in case of cool roof than dark roof. The reduction over a period of 24 hour for the entire monitoring duration is 14.41 W/m^2 and for daytime is 21.43 W/m^2. The maximum mean reduction in flux occurs in the month of April for 24 hours (18.31 W/m^2) duration as well as daytime (26.31 W/m^2). The scatter plots between cool roof and dark roof for heat flux entering the building has a slope of 0.66 which implies that cool roof has lower heat flux than dark roof.

The following tables summarize the mean, maximum and minimum reduction for over deck surface temperature, under deck surface temperature, indoor air temperature and the heat flux.

Table 1: Over deck temperature reduction in during the Jan - Jun

Over deck temperature reduction (^{0}C)						
	Mean reduction		Max reduction		Min reduction	
	24 hrs	Daytime	24 hrs	Daytime	24 hrs	Daytime
Jan	2.82	5.21	13.06	13.06	-0.04	0.09
Feb	3.74	7.19	12.36	12.36	0.00	0.72
Mar	4.48	8.53	13.77	13.77	-0.63	2.29
Apr	4.94	9.29	14.29	14.29	-0.34	2.23
May	4.59	8.78	14.12	14.12	-0.17	2.20
Jun	4.01	7.79	13.41	13.41	-0.25	0.74
Jan - Jun	4.06	7.74	14.29	14.29	-0.63	0.09

Table 2: Under deck temperature reduction during Jan - Jun

Under deck temperature reduction (^{0}C)						
	Mean reduction		Max reduction		Min reduction	
	24 hrs	Daytime	24 hrs	Daytime	24 hrs	Daytime
Jan	1.49	1.35	3.84	3.84	0.11	0.11
Feb	1.72	1.53	3.91	3.91	-0.24	-0.24
Mar	2.13	1.90	4.62	4.47	-0.07	-0.07
Apr	2.63	2.53	5.32	5.32	0.50	0.50
May	2.45	2.39	4.88	4.88	0.48	0.48
Jun	2.25	2.24	6.70	6.70	0.39	0.39
Jan - Jun	2.09	1.97	6.70	6.70	-0.24	-0.24

Table 3: Indoor Air Temperature reduction during Jan - Jun

Indoor Air temperature reduction (^{0}C)						
	Mean reduction		Max reduction		Min reduction	
	24 hrs.	Daytime	24 hrs.	Daytime	24 hrs.	Daytime
Jan	0.70	0.35	1.80	1.51	-1.39	-1.39
Feb	0.76	0.06	2.08	1.82	-1.59	-1.59
Mar	0.94	0.05	2.66	2.19	-1.64	-1.64
Apr	1.38	0.66	2.86	2.70	-1.08	-1.08
May	1.33	0.71	2.77	2.55	-0.75	-0.75
Jun	1.30	0.89	2.45	2.43	-0.47	-0.47
Jan - Jun	1.06	0.44	2.86	2.70	-1.64	-1.64

Table 4: Heat Flux reduction during Jan - Jun

Heat Flux reduction (W/m^2)						
	Mean reduction		Max reduction		Min reduction	
	24 hrs.	Daytime	24 hrs.	Daytime	24 hrs.	Daytime
Jan	8.37	12.61	40.75	40.75	-5.39	-4.76
Feb	12.68	20.15	40.86	40.86	-5.81	-1.70
Mar	16.66	26.04	47.35	47.35	-3.73	3.66
Apr	18.31	26.31	42.85	42.85	-1.05	-1.05
May	16.70	24.14	40.30	40.30	-3.02	3.61
Jun	14.61	20.39	35.04	35.04	-0.86	-0.30
Jan - Jun	14.41	21.43	47.35	47.35	-5.81	-4.76

Since the indoor air temperature reduces with cool roof comfort analysis was performed for both the buildings. The total number of uncomfortable hours was calculated for both the buildings.

The outdoor dry bulb temperatures, and comfort band (Eq 1) are summarized in the following table:

Table 5: Comfort temperature band for Jan - Jun

	$T_{outside\ dry\ bulb}$ (^{0}C)	$T_{neutral}$ (^{0}C)	Comfort low (^{0}C)	Comfort High (^{0}C)
Jan	14	21.94	18.44	25.44
Feb	17	22.87	19.37	26.37
Mar	23	24.73	21.23	28.23
Apr	29	26.59	23.09	30.09
May	33	27.83	24.33	31.33
Jun	36	28.76	25.26	32.26

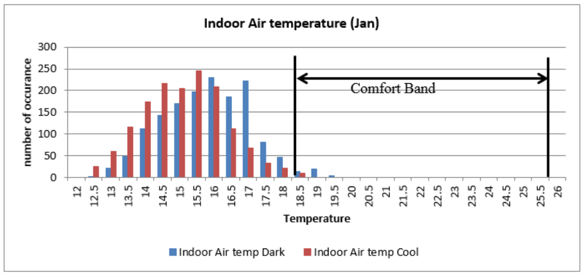
Using cool roof results in discomfort in the months of January and February and it increases the comfort in the months of March, April and it has no effect in the month of June. Though there are negative effects on comfort in winter months, the benefits from the summer months leads to a net increase in comfort. The comfort hours are summarized in the following table:

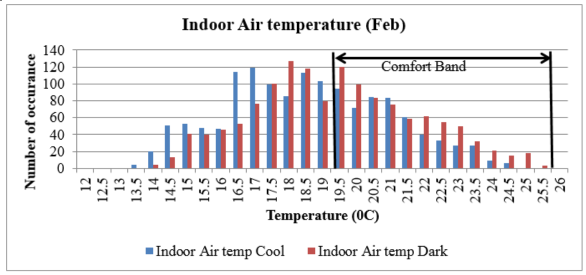
Table 6: Number of comfort hours for Jan - Jun

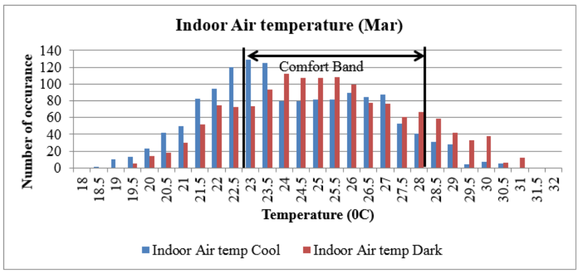
	Number of comfortable hours		Number of Uncomfortable hours		Change in comfort
	Dark roof	Cool Roof	Dark roof	Cool Roof	
Jan	12	0	732	744	-12
Feb	299	230.5	397	465.5	-68.5
Mar	591.5	604.5	129.5	115.5	13
Apr	122.5	224.5	453.5	351.5	102
May	36	83	708	661	47
Jun	0	0	672	672	0
Jan - Jun	1061	1142.5	3092	3009.5	81.5

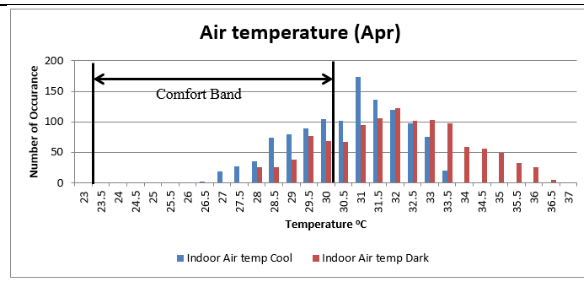
Using cool roofs reduces the peak indoor air temperature and heat flux. Histogram plots of heat flux and indoor air temperatures shows shift in the peak temperatures. Even the temperature and heat flux cluster peaks have been shifted backwards in case of cool roof compared to dark roof.

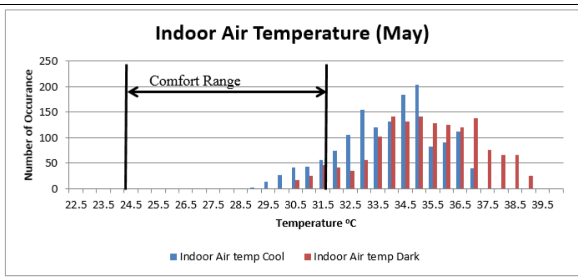
Typical histogram plots of indoor air temperatures along with comfort band for all six months are shown below:

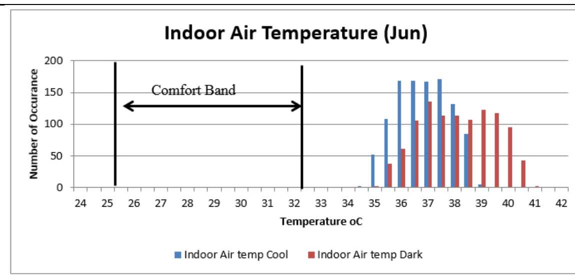












5. Conclusions

The results from the field study shows that using a cool roof (SR – 0.57) over a dark roof (SR – 0.28), results in temperature and heat flux reduction in an un-conditional institutional building. The reduced indoor air temperature levels leads to increased comfort. For the monitored period of six months (Jan - Jun), the mean reduction in indoor air temperature was 1.06^0C for 24 hours duration and 0.44^0C for the operational hours. Since there would be heat ingress in the room with cool roofs from the windows and walls that are exposed to the outside atmosphere, the savings could be higher than what is being observed in this experiment. The peak reduction in the indoor air temperature observed was 2.86^0C in 24 hours duration and 2.70^0C in the operational hours. The heat flux coming inside the building is also reduced over the entire duration. The mean reduction over 24 hours is 14.41 W/m^2 and the daytime reduction is 21.43 W/m^2.

6 Acknowledgements

We gratefully acknowledge Prof. K.P. Singh for assistance in arranging fieldwork at the G.B. Pant University. We also thank Bipin Shah (Winbuild) for arranging the roof coatings, Ken Reichl for assistance with radiometer instrument preparation and initial data reduction. This work was supported by the US DOE Offices Energy Efficiency and Renewable Energy, and the US DOE Office of Science, Atmospheric Radiation Measurement program, under contract DE-AC02-05CH11231.

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