Post-occupancy evaluation of passive downdraft evaporative cooling and air-conditioned buildings at Torrent Research Centre, Ahmedabad, India

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ABSTRACT:
Post occupancy evaluations of buildings are noted for their ability to provide vital feedback regarding a building's performance in use. In addition to obtaining physical measurements of thermal performance and energy consumption, it is crucial to obtain feedback on user experience and satisfaction with the building environment to gain a true picture of the effectiveness of low energy buildings. This paper will report findings of a study aimed at investigating building performance and occupant experience of the Torrent Research Centre in Ahmedabad, India. The Centre comprises six laboratory and office blocks, four of which incorporate a passive downdraft evaporative cooling system (PDEC). Air-conditioning is restricted to the two equipment intensive laboratories. While a number of earlier publications have reported on the configuration of the environmental control systems and the thermal performance of this building, this paper will provide insights into the occupants' experience and feedback on the building and will detail the comparative performance of the PDEC and air-conditioned blocks. Occupant perception of overall comfort (summer, winter and monsoon), temperature, air movement and quality, lighting, noise, productivity, health, design, image and workplace needs was evaluated using the Building Use Studies workplace survey.

The co-location of PDEC and air-conditioned blocks offers a unique opportunity to compare performance while overcoming issues arising from contextual differences such as conditions of work, attitudes and expectations of employees likely to occur between respondents in different countries. The findings reveal occupant satisfaction in both the PDEC and air-conditioned blocks to be well above Building Use Studies' international benchmarks. In addition to their lower energy consumption, the overwhelmingly positive user satisfaction responses of the PDEC blocks validate the integration of alternative climate control systems such as evaporative cooling in contemporary buildings in India.

Conference theme: Human issues: social, cultural, economic, thermal comfort

Keywords: post occupancy evaluation; occupant satisfaction; passive downdraft evaporative cooling

INTRODUCTION

In keeping with a rich tradition of climate responsive vernacular architecture in India, a number of passive solar and energy efficient non residential buildings have been developed over the last two decades in India (see Majumdar 2001a). These are designed and developed in response to growing concerns for minimising energy dependence in a context where increased urbanisation fuels power demand, over 30% of the electricity energy is consumed in commercial and domestic buildings and air conditioning (AC) accounts for 50% of energy use in modern commercial buildings. (TERI 2005). The Torrent Research Centre Building in Ahmedabad completed and occupied in 1997 has been widely reported as a unique example for climate responsive design which integrates a passive downdraft evaporative cooling system. A detailed description of the design process, building configuration, environmental control system and thermal performance can be found in an earlier study completed by Baird (2001). The building was revisited at the end of 2004 by the authors with the aim of investigating building performance and occupant experience.

1 POST OCCUPANCY EVALUATION METHODOLOGY

Post occupancy evaluations of buildings are noted for their ability to provide vital feedback regarding a building's performance in use. In addition to obtaining physical measurements of thermal performance and energy consumption, it is now widely recognised that feedback on user experience and satisfaction with the building environment is necessary to gain a true picture of the effectiveness of low energy buildings. (BRI 2001)

The present study comprised of a site visit of the building while in use, interviews of key stakeholders (architect, consultant, and client) and the administration of an occupant survey. In addition information regarding energy consumption was sourced from the building owner occupier based on in house metering and energy bills, and information as to temperature monitoring was sourced from previous studies.

The occupant survey used was the Building Use Studies Survey (BUS) Workplace Questionnaire. The BUS questionnaire is a post occupancy evaluation instrument developed by Building Use Studies, UK. The BUS survey method was originally developed for the Office Environment Survey (Wilson and Hedge,1987), and then adapted for the PROBE (Post-occupancy Review Of Buildings and their Environment) project (1997-2002) in the United Kingdom published through the *Building Services Journal*. The database comprises over 260 buildings worldwide. The two page paper based 'standard' questionnaire was selected for its capacity to provide feedback on a range of 63 variables covering aspects of overall comfort, temperature, air movement and quality, lighting, noise, productivity, health, design, image and workplace needs. While the standard questionnaire includes questions relating to comfort, temperature and air in summer and winter, they were mirrored to cover the monsoon season when many parts of the Indian subcontinent experience hot humid conditions.

The results for the BUS Survey are documented under Section 0. Unless stated otherwise responses to the variables discussed are sought on a 7 point scale. Analysis of these responses yields a mean value which may be simply assessed in relation to the selected scale, or compared with the mean value from the BUS dataset benchmark together with the its upper and lower 95% confidence intervals (which are based on the previous 50 buildings analysed). In the subsequent discussions reference is made to three types of scales:

- A type scale where better values are found towards the "right hand" of scale, 1 = worst option, 7 = best option
- B type scale where better values are found towards centre of scale, 4 = best option
- C type scale where better values are found towards the "left hand" of scale, 1 = best option, 7 = worst option.

It should be noted that the results are not derived for example from estimations for thermal comfort that may be derived by applying calculation methods such as PMV (Predicted Mean Vote after Fanger, 1970) or adaptation models (after Auliciems, 1983) to monitored temperature data, rather the mean scores and open ended comments provide a rich description of users' experience and assessment of temperature, air, noise, lighting and comfort overall.

Based on extensive research the developers of BUS (Leaman and Bordass 2005) have noted that perceived productivity as used in the BUS survey is considered the best available indicator (as opposed to number of sick days, or number of key strokes that can be achieved within a set time frame) that is common to all respondents in a building, and enables comparison across buildings.

The BUS survey enables the use of benchmarks to assess how perceptions in individual buildings score against the complete data set, nevertheless it should be noted that Torrent is only the second building to be surveyed using the BUS methodology in India. Regional benchmarks will be necessary to make more context specific comparisons or conclusions. Nevertheless the co-location of PDEC and air-conditioned blocks at Torrent offers a unique opportunity to compare performance while overcoming issues arising from contextual differences such as conditions of work, attitudes and expectations of employees likely to occur between respondents in different countries.

The survey was administered to occupants of the Torrent Research Centre in December 2004. A total of 292 surveys were distributed and 164 responses returned.

2 BUILDING DESIGN PROCESS AND OUTCOME

Figure 1 Plan and section of a PDEC Bulding

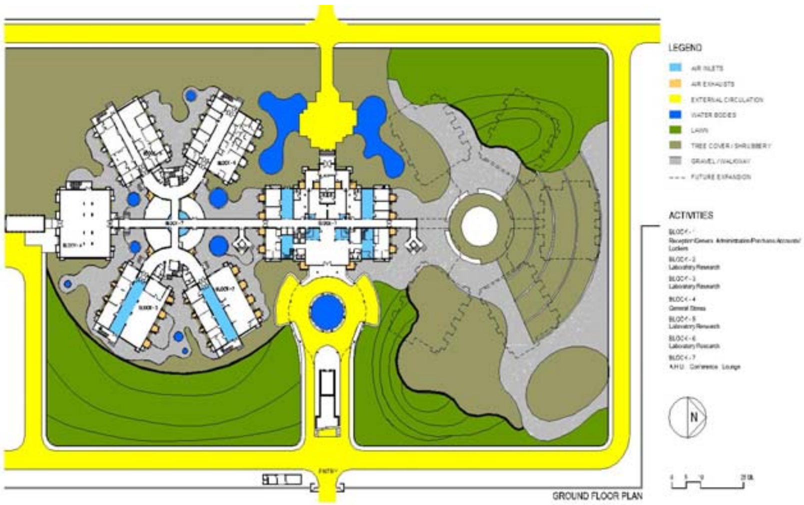


Figure 2 Torrent Research Centre – Layout Plan

Figure 3 Torrent Research Centre –
(drawings and photo courtesy: Abhikram)

The TRC complex is comprised of a range of pharmaceutical research facilities and related support services, housed in a group of a dozen or so buildings. This study was focussed on the main group of five three-storey laboratory buildings and one administrative block radiating from a circular-plan core building (see Figure 2). Started in 1994, construction was completed by 2000, the laboratories having been occupied progressively since the latter part of 1996.

Principal architects for the project were the husband and wife team of Nimish Patel and Parul Zaveri practicing under the name of Abhikram since 1979. From the outset, they resolved that all of their buildings would be able to work during daylight hours using the minimum of electrical energy. In time, this objective evolved into one of the practice's six statements of basic design philosophy, viz, 'Conservation of resources is the primary guideline for all the projects' (Abhikram 1998). Environmental design consulting services for the typical laboratory block on this project were provided by the London-based firm of Short + Ford Associates who had carried out pioneering work on natural ventilation systems in Europe. The design served as a prototype for the remaining laboratory buildings and administrative buildings that were developed and detailed by Abhikram with assistance from Solar Agni International, Pondicherry. The design of the more conventional air conditioning systems, for those parts of the building which required them, was undertaken by engineering consultant Mr M Dastur of New Delhi, while the design and construction of the water spray used in conjunction with the natural ventilation system was carried out in-house by Torrent's Assistant General Manager (Engineering) Mr S B Namjoshi, and his team.

The Board of Torrent Pharmaceuticals Ltd. had decided to make a major investment in research and needed a new facility in order to expand this aspect of their operation. They also proved willing to embrace the Abhikram design philosophy. From the environmental point of view, the intent was to maximise the use of natural light and ventilation, use locally available natural materials, and control the ingress of dust. All of which was a fairly tall order in a climate with three distinct seasons - hot and dry from March to June with temperatures reaching well over 40^{O}C, warm and humid from July to September during the monsoon, and cool and dry from October to February, the 1 per cent values ranging from $+12.8^{O}$C in the cool season to $+41.0^{O}$C in the hot (ASHRAE, 2001: 27.36-7). With the appointment of Abhikram as architects for the Centre, designing of the first laboratory block commenced in early 1992. A central corridor concept, with working spaces on either side, was developed and the Passive Downdraft Evaporative Cooling (PDEC) method of cooling adopted for the final design in February 1994. In this scheme the air was supplied via the central corridor and exhausted at the perimeter as indicated on Figure 1.

While many aspects of environmental design were taken into account, Dr C Dutt, Torrent's Director of Research, was quite prepared to take a wait and see position on some issues - for example, on the questions of the potential for rain penetration via the ventilation towers, or for lack of air movement in some locations. He was also open to the concept of designing for a threshold temperature (28-28.5ºC) which could be exceeded for a certain number of hours, rather than some absolute value. In this connection, the designers were unstinting in their admiration for him as a critical, but immensely supportive client (Chauhan, 1998).

Clearly, a number of factors such as client commitment for environmental design, clear goals for environmental performance, an integrated multidisciplinary team approach to design that is mindful of user needs, and responsive building management during commissioning and operation, that have been argued to influence low energy outcomes (Thomas and Hall 2004) are all evident in the development of the Torrent Research Centre.

Each laboratory building has a similar 22m by 17m plan, with a 4m wide corridor flanked by 5m deep office spaces and 8m deep laboratory spaces (see Figure 2). Two of the five laboratory buildings are air conditioned, the other three equipped with the PDEC system. The larger main administrative building (see Fig 2) is located to the north of the laboratories, and a utilities building to the south, with a two level corridor spine linking. The entire complex covers 22,600m^2 of floor space, of which around 3,200m^2 is air conditioned. The central plant for this research facility includes two oil fired steam boilers with a capacity of 4T/hr each, two 175cfm air compressors, two 725KVA diesel generator sets, and some 350 Tons of refrigeration capacity.

Overall control of solar heat gains is achieved by judicious design of the glazing., The fixed windows are shaded externally, not only in the horizontal plane by overhangs, but also in the vertical plane by the air exhaust towers which project from the façade. The buildings are thermally massive - the reinforced concrete construction framed structure has cavity brick infill walls, plastered inside and out, and hollow concrete blocks filling the roof coffers, also plastered inside, with vermiculite used as an insulating material on both roof and walls . External surfaces are white - the walls painted, the roof using a china mosaic finish.

The critical climatic time of the year is the hot dry season when mid-afternoon outside temperatures regularly reach $40^{O}C$ or more. These are the conditions under which the PDEC system is designed to operate. It does so by piping water through nozzles at a pressure of 50 Pa to produce a fine mist (dubbed the 'microniser' system by Brian Ford) at the top of the three large air intake towers located above the central corridors of each laboratory building. Evaporation of the fine mist serves to cool the air which then descends slowly through the central corridor space via the openings on each side of the walkway (see Figure 1). At each level, sets of hopper windows designed to catch the descending flow, can be used to divert some of this cooled air into the adjacent space. Having passed through the space, the air may then exit via high level glass louvred openings which connect directly to the perimeter exhaust air towers. Night time ventilation is also an option during this season.

During the warm humid monsoon season when the use of the microniser would be inappropriate, the ceiling fans (introduced to ameliorate the muggy conditions experienced during the first monsoon season) can be brought into operation to provide additional air movement in the offices and laboratories. In the cooler season the operating strategy is designed to control the ventilation, particularly at night, to minimise heat losses - this is done simply by the users adjusting the hopper widows and louvred openings in their individual spaces to suit their requirements.

Each of the building blocks surveyed was originally designed for an occupancy of 25 scientists. With the expansion of activities, increase in staff and overlapping shifts in recent years, some of the buildings currently house as many as 70 – 80 people working at the same time.

3 POST OCCUPANCY EVALUATION OUTCOMES

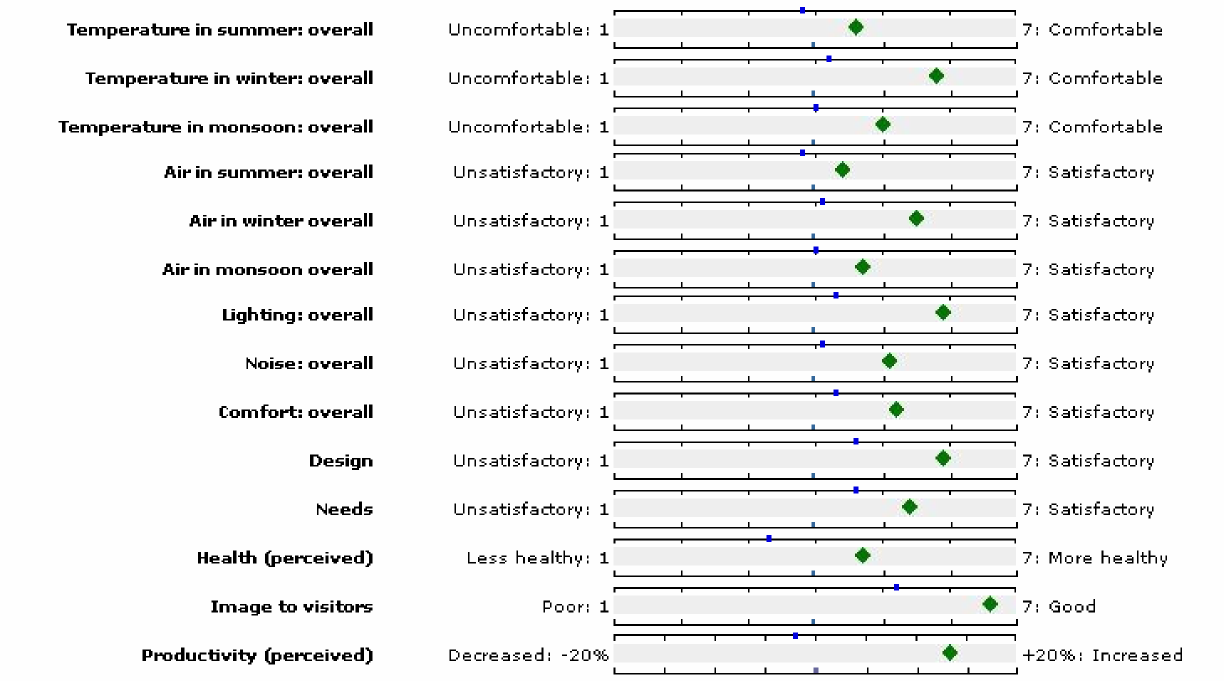
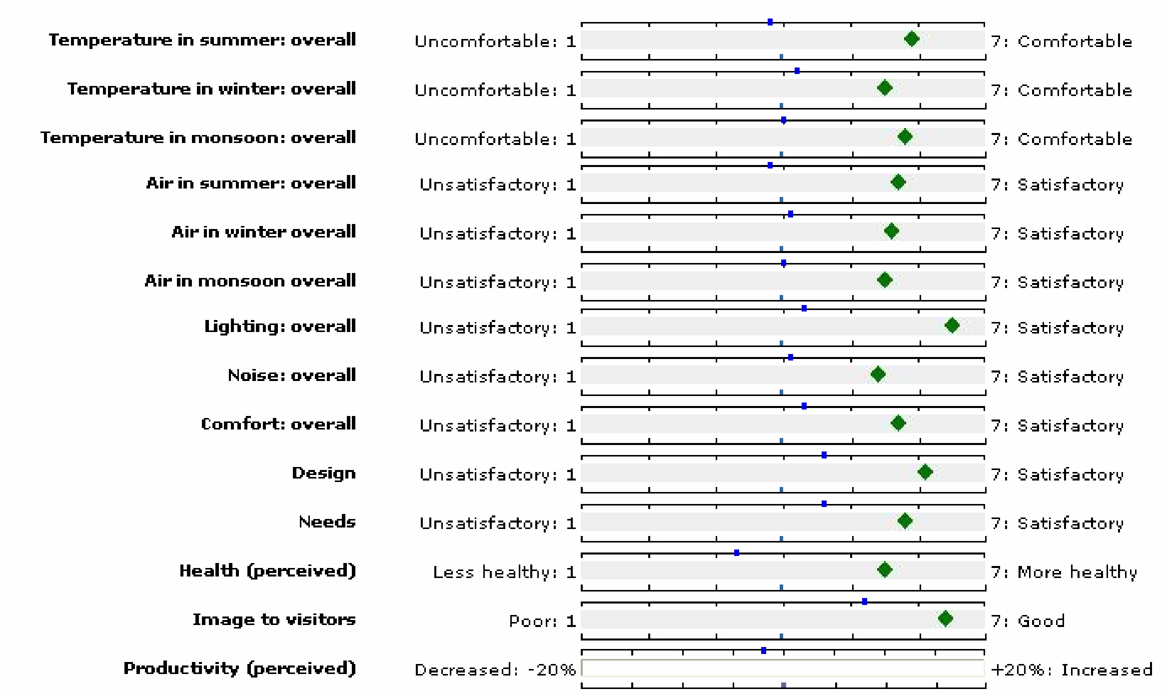


Figure 4 Building Use Studies Summary Chart for PDEC Buildings at Torrent Research Centre 100 respondents – December 2004.



Perceived productivity for air conditioned buildings was rated at +20.88%

Figure 5 Building Use Summary Chart for AC Buildings at Torrent Research Centre 64 respondents – December 2004.

Key to BUS Summary Charts

These are summaries of some of the variables used in Building Use Studies building occupant assessments.
Green diamonds represent mean values significantly better or higher than both benchmark and scale midpoint (a good score). Amber diamonds are mean values no different from benchmark and scale midpoint (a typical score). Red diamonds are mean values worse or lower than benchmark and scale midpoint (a poor score).
Benchmarks are represented by the small blue rectangle on the top scale of each variable. They are drawn from British, Australian and International datasets, depending on context. There are no benchmarks available for monsoon season as yet. All of the summary variables above are rated on a (A type) 7-point scale where 7 is best and 1 is worst. © Building Use Studies 2005

Figure 4 and Figure 5 represent the summary performance of the building for critical variables. As evident both the PDEC blocks and the AC blocks returned mean scores that were significantly better or higher than both benchmark and scale mid-point for all of the categories. While regional benchmarks will be necessary to make more context specific comparisons or conclusions as previously noted, the consistently positive responses with respect to international benchmarks and scale mid-point is certainly worthy of note. Detail results are discussed below.

3.1 Temperature, Air Quality and Overall Comfort

As noted the PDEC buildings were developed with an approach towards designing for a threshold temperature around 28ºC which could be exceeded for a certain number of hours. Previously monitored temperatures in 1997 and 1998 have indicated that internal maximum temperatures could be maintained 12-14 degrees below the external peak and that internal temperatures were around 5 degrees lower than average external temperatures (Baird 2001). Ford (1999) reports temperatures of 27ºC to the ground floor and 29ºC to the first floor with outdoor temperatures at 38ºC and Majumdar (2001 b) reports temperatures of 29-30ºC being achieved when temperatures reach 43-44ºC. Majumdar also reported temperature fluctuations did not exceed a 4 degree range over any 24 hour period, when temperature fluctuations outdoor were has much as 14-17 degrees. One of the early issues noted was a tendency for air to by pass the top floor (Ford et al 1998)

As seen in Figure 4, overall ratings of summer and winter temperatures are significantly higher than the midpoint and benchmarks for both the PDEC buildings (summer 4.61, winter 5.84, A type scale). This is also the case for overall Air conditions (summer 4.44 winter 5.54) and Comfort overall (5.16). The overall results for Temperature Air and Comfort for PDEC in this survey corroborates earlier reports that “comfort conditions have not been compromised” (Majumdar 2001 b). Figure 5 shows similarly positive results for the air-conditioned buildings.

Figure 6 shows occupants consistently rated temperatures on the colder side of neutral (mid point of a scale of too hot – too cold) in the air conditioned buildings. The mean scores for air conditioned buildings were 5.86 in summer, 5.29 in winter and 4.66 in monsoon on a B type scale of 1 to 7 where 1 = too hot and 7 = too cold. This is not surprising given that the controlled air conditioned labs are maintained at temperatures around 22-24ºC in comparison to a more adaptable range of generally 5 degrees less than the outside mean temperatures in the PDEC buildings. On the same scale the means scores for the PDEC buildings are close to neutral in monsoon and on the colder and warmer sides of neutral in winter and summer respectively.

The overall satisfaction for Comfort, Air Quality and Temperature seen in the PDEC buildings, particularly in context of acceptable temperature ranges that are much higher than those deemed acceptable in western contexts is worthy of further study.

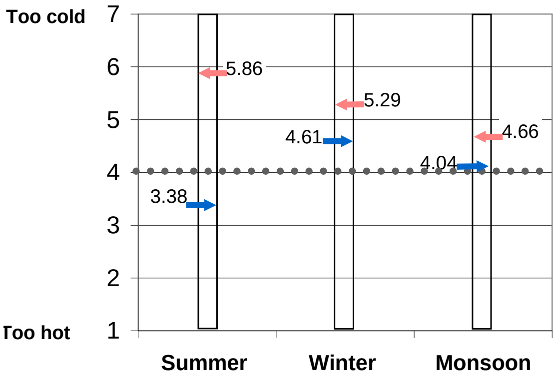


Figure 6 BUS Results Temperature (too hot/cold)

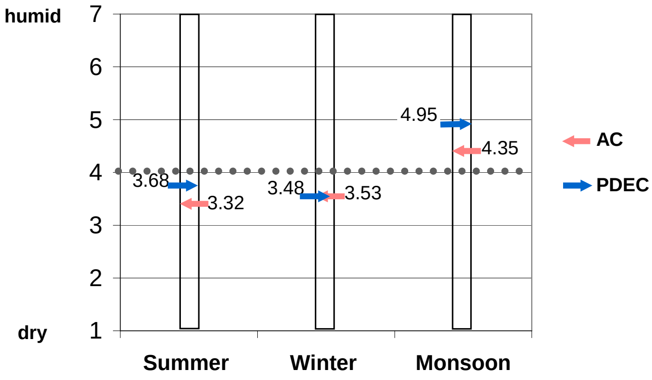


Figure 7 BUS Results Air (dry/humid)

The performance of the building in the monsoon season was of particular interest in the PDEC buildings. Following the first year of occupancy ceiling fans were installed as a consequence of the experience of "muggy conditions" in the building as noted by the client (Dutt, cited in Majumdar 2001 b). Occupant responses for this season were generally positive. In addition to the above midpoint values for overall satisfaction with temperature (Figure 4) and close to neutral rating of experienced temperatures (Figure 6), occupants experienced some concern about air humidity (Figure 7, 4.95 on a B type scale 1 = dry and 7 = humid) and moderate satisfaction with overall air conditions in monsoon(4.68 on an A type scale 1 = unsatisfactory, 7 = satisfactory).

Open ended comments to comfort and ventilation arising from both PDEC and AC blocks were predominantly positive, Comments from the PDEC included *"Everything in this building is well equipped for work and comfort*" (PDEC) *"Satisfactory, well ventilated good infrastructure" and "Good ventilation".* Nevertheless there are some experiences of discomfort in summer for the PDEC buildings: *"If summer can be taken care of this will be a wonderful place to work at" (PDEC),* as well as some concerns about odours during this period *"Stuffy in summer with lots of odour and poor ventilation".* It is likely that the increase in internal heat gains and latent loads from increased occupancy (see section 2) in the PDEC buildings results in more incidences of internal conditions sliding above a acceptable levels, particularly when temperatures peak outdoor in summer. Monitoring of temperature conditions and ongoing changes to occupant needs coupled with evaluations of user experience is necessary to study this in detail.

3.2 Lighting:

Both types of buildings performed well in terms of overall lighting. Figure 4 and Figure 5 indicate there was general satisfaction with the lighting conditions overall. (PDEC = 5.86, AC = 6.46 on a A type scale 1 = unsatisfactory, 7 = satisfactory)

Both the PDEC and the AC buildings had similar configurations in terms of layout, window to wall ratios and access to daylight. Not all workstations received natural light and this was evident in some of the individual open ended comments:
"Natural light is insufficient"; (PDEC)
"Lighting is very good at TRC. Whether it is natural or artificial is up to the [location] of work" (PDEC)
"Lighting is good, natural light is less" (AC)
Nevertheless the detail scores for natural light (B type scale, 1 = too little to 7 = too much) were close to mid point - 3.82 for PDEC and 3.96 for AC. Artificial lighting on the other hand rated closer to the "too much" end of the B type scale, with PDEC = 4.86, and AC = 4.79. The building also rated well for minimum glare from the sun and sky. The overall satisfaction with natural lighting is particularly noteworthy given the low window to wall ratios of the facades, coupled with provision of diffused daylight to the central walkways and offices adjoining air inlet/outlet towers.

3.3 Noise:

Open ended comments suggest that there were minor issues with noise from colleagues, inside and from other people, however as evident in Figure 4 and Figure 5, there was general satisfaction with the noise conditions overall. (PDEC = 5.09, AC = 5.39 on a A type scale 1 = unsatisfactory, 7 = satisfactory) The green-field setting of Torrent buildings on the outskirts of the city, has meant there are no particular issues with noise from external sources even in the buildings with openable windows and PDEC systems installed.

3.4 Control

In the PDEC buildings, occupants are able to adjust hopper windows to inlet towers and louvers, operate ceiling fans and switch on lights. Responses show a perceived lack of control for cooling heating ventilation and noise (more or less about the mid point on a A type scale 1=no control and 7=full control) and low rating of importance for control (under 20% rated control as important). However as evident in sections on Comfort and Productivity, this had little impact on overall comfort and perceived productivity. This would corroborate Leaman and Bordass' findings (2005) that the strength of the relationship between perceived control and productivity decline as the buildings perform better.

3.5 Design Needs and Image to visitors

As noted elsewhere (Baird 2001) the building is distinguished for its overt expression of thermal environmental control systems. The nature of the design process which involved a close collaboration of the users and the design team has been discussed previously (see Baird). The recent site visit revealed that all current users were very aware of the design intent of the building and were appreciative of its unique ventilation and cooling systems and appearance.

Users across all the buildings blocks and functions were consistent in their high rating for Design and Image to visitors. In addition, they rated the building highly for its ability to satisfy their needs (5.44 in PDEC and 5.79 in AC, A type scale) overall. Mean scores were also consistently better than benchmark and scale midpoint for aspects such as cleaning, availability of meeting rooms, space in the building, space at the desk, storage space and furniture.

3.6 Health and Productivity (perceived)

Interestingly, the mean responses for both PDEC and AC suggest users at Torrent feel more healthy when they are in the building (4.74 in PDEC and 5.53 in AC, A type scale see Figures 4 and 5). In addition, the building returned “off the scale” perceived productivity rating of +20.88% for AC and +13.66% for PDEC. Positive responses to both heath and productivity were corroborated by majority of the open ended comments.

Leaman and Bordass (2005) identify the following “killer variables” that produce positive correlations with productivity: positive responses to comfort, responsiveness to need, clarity of design intent to users, robust ventilation and air conditioning systems, and attention to designing for workplace needs. With all of these factors present in the Torrent building, the positive results for perceived productivity reinforce the value of these influencing factors in shaping users' experience.

3.7 Energy

The total energy consumption for PDEC and AC combined (includes light, equipment and AC for 2 blocks) for the 6 blocks in 2005 was 647000 kWh[1]. This averages to 54 kWh/m^2 and 72 kgCO_2/m^2 (based on a floor area of 12000m^2 for the surveyed buildings and a greenhouse gas coefficient of 1.34 (ABGR, 2003) for brown coal fired electricity). Clearly the climate responsive approach to building design has resulted in a high level of energy savings. In the absence of benchmarkable data for buildings such as Torrent comprising labs and offices with extended hours of operation in hot dry climate in India, the building is compared to available targets for commercial buildings - The Torrent energy consumption performance compares very favourably to the target for newly developed fully air conditioned building currently set in not to exceed 140 kWh/m^2 for day use in a composite climate under the recently introduced environmental rating scheme TERIGRIHA and reported typical consumption in Indian buildings of 280-500kWh/m^2.a or 375-670 kgCO_2/m^2. based on GHG coefficient of 1.34. (Singh and Michealowa, 2004).

4 CONCLUSIONS

The Torrent Research Centre demonstrates excellent environmental outcomes. The findings outlined in this paper show that this building, completed over 10 years ago, continues to satisfy expectations for a contemporary workplace of high quality that is simultaneously energy efficient. While the wider implications of the success of such buildings for the Indian subcontinent where there is currently a large scale development of “glass boxes” that are both energy intensive and inappropriate for the climate are discussed in a paper by Thomas (2006), clearly the building performance outcomes in Torrent reinforce the value of a climate responsive approach to building design in any location.

Even in those situations where air-conditioning is inevitable, the climate responsive design coupled with a user responsive approach to design, commissioning and ongoing management is a model worth emulating for future buildings in order to achieve buildings that are both energy efficient as well as capable of enhancing work place quality. Although the air conditioned buildings produced somewhat better results than buildings incorporating the passive downdraft evaporative cooling systems in the BUS survey, it is important to note that the BUS results of the PDEC buildings were also consistently better than international benchmarks and scale mid-points. Further study is anticipated to establish regional benchmarks, however the overwhelmingly positive user satisfaction responses of the PDEC blocks coupled with their lower energy consumption validate the integration of alternative climate control systems such as evaporative cooling in contemporary buildings in India.

5 ACKNOWLEDGEMENTS

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We would like to acknowledge Adrian Leaman for permission to use the BUS questionnaire under licence, and for his feedback and support during the project.
This paper also draws on earlier research conducted by Professor George Baird including interviews at the time with Nimish Patel (Abhikram) and Brian Ford (Short + Ford Associates). A number of individuals associated with the Torrent

1 Source: 2006 Communication from Dr C Dutt, based on in- house metering and electricity bills.

Research Centre have been of great assistance. We wish particularly thank Dr C Dutt for providing access to the building, monitored data, and permission to survey the occupants. The present study would not have been possible without the interest and participation of architects Nimish Patel and Parul Zaveri (Abhikram) who gave their time generously to participate in interviews and provided drawings as well as information relating to the design development of the building included in this paper.

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