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ENVIRONMENT DESIGN GUIDE

CLIMATE RESPONSIVE DESIGN: COOLING SYSTEMS FOR HOT ARID CLIMATES

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Emilis Prelgauskas (B.Arch RAIA) is in sole practice in South Australia, emphasising sustainable solutions and emergent technologies. Across a quarter century, this practice has contributed to evolving thinking on low-energy cooling systems and trialled, prototyped and embedded these systems into its building elements, with post-occupancy measuring of selected examples. Emilis is refereed as building energy expert to the SA Government Building Rules Assessment Commission and chairs the SA Chapter AIA Environment working party.

Abstract

In hot arid climates, cooling is the dominant need in order to attain comfort. This paper highlights the natural forces (wind, solar gain, moisture) that can be harnessed for cooling, and the resulting passive building elements which contribute cooling effect when integrated into the built form. With these, natural ventilation and cooling can achieve comfort lessen or even obviate the need for mechanical air-conditioning.

The systems described were originally published in EDG papers DES20 and DES59. This paper consolidates and updates the information.

The Mediterranean courtyard of the old Treasury, Adelaide – a natural air-conditioning device
(Image: Medina Grand Adelaide Treasury)

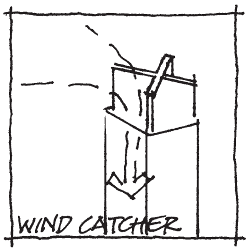
INTRODUCTION

Design of buildings and external spaces in hot arid climates can integrate building elements which achieve cooling effects that lessen or even obviate the need for mechanical systems.

The systems described in this paper achieve cooling flows greater than conventional openings for wind-driven ventilation. Their cooling effects mitigate heat inflows through building envelope insulation and openings, and internal heat emanating from thermal mass elements, appliances and occupants. In reducing the need for energy-intensive cooling systems, they will also lead to increased energy efficiency.

One caveat is that many systems are dependant for their optimal functioning on occupant behaviour, therefore this paper explores some of the factors which promote occupant engagement with climate responsive systems.

Traditional Cooling Devices



Indigenous societies in hot arid lands have historically developed a range of passive and low-energy, interior comfort elements including wind catchers, solar up-draught towers, and single-room depth buildings with surrounding courtyards with sunny area paving and shade area fountain elements that function as air-conditioners.

Traditional buildings in Middle Eastern and Asian arid lands have incorporated a number of further evaporative air-conditioning elements consistent with the technology of the day: linen drapes wetted and unfurled across openings, and water-filled porous clay pots placed in high locations in rooms or in down-draught towers.

Many of the climate responsive building elements we list in this paper are adaptations of these traditional devices.

CLIMATE RESPONSIVE BUILDING DESIGN

Climate responsive design is a complete system extending on from passive solar. It uses three prominent, naturally occurring atmospheric forces to achieve building ventilation and cooling:

- Solar heating and consequent air flow through thermal convection
- Changes in atmospheric pressure arising from wind flow over objects creating secondary air flows
- Changes in the flow rate and latent heat capacity of air by introducing moisture to the air

Conventionally, solar heating has been considered the enemy of comfort in hot arid locations. Solar heat will generally penetrate the building structure on long, hot days – with human occupation and appliance operation adding to interior heat load. The result is that the building becomes too hot for comfort later in the day, even after prior night purging.

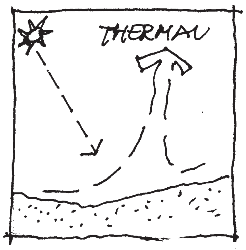
The natural ventilation schemes outlined in this paper provide follow-up strategies for maintaining interior comfort once that initial nighttime 'coolth' has been exhausted.

How It Works

Solar heat instigates air flow by thermal convection. Winds can create indirect airflows. In arid locations, the normally very low ambient humidity enables added moisture to cause airflow and a sense of cooling. Elevating the air water content to 35 to 40 per cent enhances cooling while avoiding interference with body cooling efficiency through evaporation of perspiration.

These forces are harnessed in a number of building design elements whereby naturally occurring, enhanced cross ventilation can be designed into buildings. As these systems generally use little or no energy input, the designing-in of these building elements produces energy efficient buildings in hot arid locations.

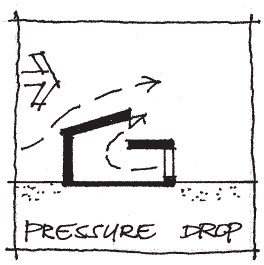
Thermal Convection



Air in external spaces can be solar heated to temperatures higher than ambient. This results in an expanding air volume, which is lower in air density than the surrounding ambient air. This imbalance is solved by thermal convection. The lighter air streams upward either as a bubble or a funnel shaped column, being replaced by ground level horizontal air inflow which in turn is sun heated, repeating the process.

This naturally occurring action can be designed into a project site as either an external courtyard or an internal greenhouse space linked to the occupant spaces. Air drawn away is then in part replaced from adjacent occupant spaces, resulting in enhanced cross ventilation within the occupied building spaces at flow rates greater than natural infiltration could achieve.

Air Pressure Modification



Air flowing over an obstacle, including a building, will modify in flow speed and air pressure relative to various parts of the obstacle's surface. Broadly, air pressure at upwind surfaces will be higher than ambient pressure while sheltered or leeward places will be at lower pressure.

These effects can be utilised to promote interior cooling. Air flow in the lee of roof ridges is at lower than ambient air pressure. Vents there will draw air from inside the building. In arid lands where summer winds are (hot) northerly, these openings could be in a south facing clerestory where an additional benefit is natural daylighting to the centre of the building interior without direct solar heat gain.

This approach is the reciprocal of the 'passive solar' sunward facing clerestory in cool climates seeking to attract additional direct interior solar heat gain,

Humidification

Adding moisture to ambient air in arid locations both increases its mass and its latent heat capacity. This is the basis of all evaporative air-conditioning. However, systems using natural means take advantage of the tendency of humidified air to sink to ground level, to 'lean' against ambient air and press it aside through its increased mass.

Such air volumes are suitable for replacement inflow air to occupied building spaces where stale air is being exhausted by thermal convection or air pressure modification.

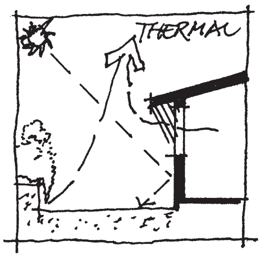
Heated air on the sunward side of the building exerts an outward suction, and humidified air from the shade side of the building will roll in to replace the hotter, drier air sucked out. Together this mix of actions creates air change within the building. The cooling sensation of the flow of the replacement air results in occupant sense of comfort in the building spaces, while the sunward 'generating' spaces adjacent, such as a greenhouse, will be outside comfort range.

DESIGN ELEMENTS

The design elements considered below fall into one of two general categories – heat extraction and cooling inflow. Naturally, best performance in climate responsive design is achieved where each element is consistent with an overall building design strategy incorporating correct orientation, insulation, thermal mass, and congruent warm and cool climatic spaces.

Thermal Courtyard

(Heat Extraction)



Ground adjacent to a northerly face of a building is subject to solar heat load both from direct sunlight and reflected heat from adjacent surfaces, notably the building exterior itself. The air in this location reaches temperatures higher than ambient, and vents vertically by thermal convection. From this pressure reduction at ground level, suction draws ground level air in from all around, including through abutting openings in the adjacent building itself.

Through this mechanism, cross ventilation is enhanced within the building, with replacement air inside the building coming from the shaded spaces around the building as described in the cooling inflow section below. The suction effect can be maximised by the thermal courtyard layout featuring heat reflection surfaces on the courtyard paving and adjacent building walling, whilst light matt colours minimise glare to other places and heat gain to the building structure.

Constructing the thermal courtyard in a sunken profile, or surrounding it with garden wall or low growing vegetation, minimises the intrusion of general wind effects which can distort the thermal convection effects being sought.

Clerestory

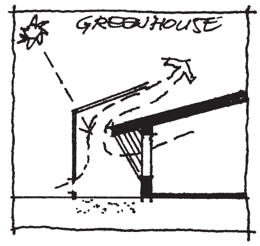
(Heat Extraction)

Passive solar can feature a north-facing clerestory to increase heat gain along with direct natural light into the building. In hot arid locations, indirect natural light into the centre of the building is attractive as a means to balance room light levels and avoid eye strain when facing the external glare from building perimeter windows. In these circumstances, a south-facing clerestory secures the natural lighting objectives without glare or direct heat gain. Such building form also provides opportunities for openings at the low-pressure portion of the building roof shape in relation to summer winds. Air from the occupied spaces can be drawn outward via the south-facing clerestory using the rooftop suction from northerly winds which are otherwise unusable, being hot, dry and embedded with dust. Replacement air is drawn from the south ground-level protected spaces adjacent to the building.

Greenhouse

(**Heat Extraction)**

The traditional greenhouse is a solar-heated space either for comfort in cool climates, or for enhanced propagation of vegetation not native to the location. The climate responsive approach in hot arid lands continues to use the greenhouse as a food production location. In addition, it uses the high air temperatures generated within to vent air out of the greenhouse,



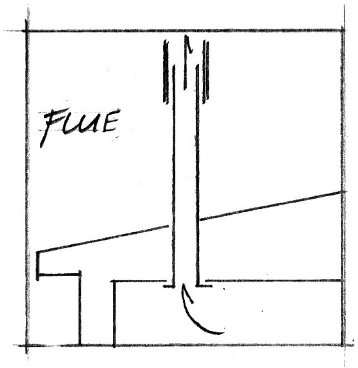
forming a natural suction pump whereby air can be drawn across from the adjacent habitable building spaces. The greenhouse itself is not a habitable space.

Such a greenhouse mechanism requires appropriate orientation to the north, a sloping roof to high-level vents, large connecting openings from adjacent habitable spaces, and low-level air intake vents from outside. In contrast to a cool climate greenhouse, there is little heat transfer from an arid land's greenhouse to the adjacent habitable spaces. The airflow from habitable space to greenhouse to outdoors draws air and heat from the habitable space and opposes infiltration of hot air from the greenhouse toward the habitable space.

Adequate insulation of directly separating walls is required. To further reduce any possible heat load on these walls, the low-level external inflow vents can be used in conjunction with the high level exhaust ones to vent hot air from the greenhouse. This mechanism is useful when the interior space is relatively cool and air is not being drawn from the interior into the greenhouse.

Thermal Flue

(Heat Extraction)

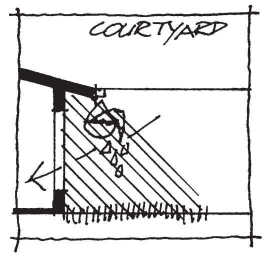


A thermal flue rises from the interior ceiling to above roof level. Solar heat gain inside the flue results in air exhaust from the flue top, which drives the outflow of interior air through the flue. Air exhaust from the interior by stack effect encourages cross ventilation within the building interior. Flue construction is either sheet metal or glazed perimeter with dark surface colour, with the option of internal thermal mass within.

Cooling Courtyard

(Cooling Inflow)

The traditional Mediterranean courtyard layout is sometimes viewed as a lifestyle design element suited to temperate climates. In hot arid climates, the Mediterranean style of a single-room depth building surrounding an inner courtyard can also be a pragmatic air-conditioning solution. The cooling courtyard abuts the shade side of the building. In an appropriately sized layout, the building volume on the north (sunny) side of the courtyard shades the immediately abutting portion of the courtyard to the south while leaving the



far southerly portion of the courtyard in direct sun. This creates a cooling zone in the shaded part of the courtyard and a thermal convection exhaust zone in the other part within the one courtyard. The portion of the courtyard in shade adjacent to the building holds air at less than ambient temperature. This air 'leans' against the building, flowing inward as replacement to that venting out the northern side of the building. The cooling effect of this air movement is enhanced by moisture transpiration from vegetation within the shaded portion of the courtyard. Such vegetation might include grasses, hanging baskets and deciduous pergola vines. Active humidifying systems there can include waterfalls, form flows, a fountain, and drippers or sprays.

Occupants perceive cooling from the achieved continuous, low-speed flow of this somewhat humidified air, even when the temperature of the incoming air is lowered only a little below ambient. Layout of features in courtyards for comfort conditioning therefore is not symmetrical, with fountains offset into the shaded portion, and paving in the sunlit portion. Relative positioning of these features is determined by the sun angles specific to any particular location. A good example of such a climatic response design is the courtyard of Medina Grand Adelaide Treasury, Adelaide, the former Treasury building begun in 1858 by architects Hamilton & Owen Smyth.

Thermal ventilation continues to function in the sunlit portion of the courtyard as described above. In a multi-building complex then, it is possible to establish a succession of thermal and cooling courtyards to maximise natural cross ventilation.

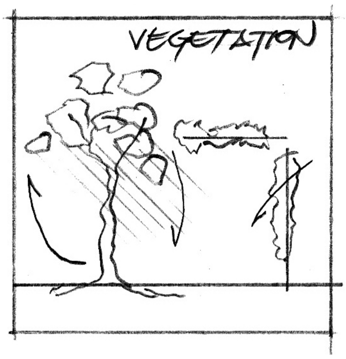
The cooling courtyard can be extended by incorporating additional shading cover such as a pergola structure. Such an extension provides additional benefit around the summer solstice, when the sun is highest in the sky, by increasing the volume of air shaded from solar heat. It is also possible to add air in-flow to the courtyard by addition of a subsidence tower with opening into the courtyard – in effect an outdoors air-conditioner.

The Wescott house in Cherry Gardens, SA. Completed in 2009, it features a fully-functional subsidence tower built into the design.

In contrast, courtyards laid out to symmetrical visual parameters alone do not accrue any of this comfort conditioning potential. Centrally placed fountains balance the ambient temperature and humidity across the courtyard, reflective surfaces add radiant heat into the shade portion of the courtyard. The atmospheric structure then tends toward stasis. The courtyard gains its own 'inversion', trapping air within the courtyard, which itself then is not a habitable space in hot arid locations.

Vegetation

(**Cooling Inflow)**



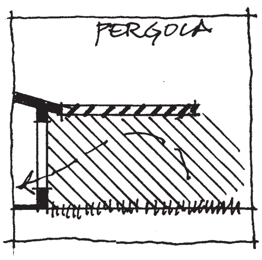
While consideration of passive solar comfort tends to focus on built form elements, vegetation also offers an integral contribution to passive cooling via moisture transpiration, creating solar load shading, and adding to insulation by creating a microclimate and additional layers to the building envelope.

Australian indigenous vegetation often has a diffuse canopy leaf structure, contrary to European expectations of dense foliage for shading. The diffuse canopy permits thermal air venting through the canopy from the sunlit ground on the northern side of the trunk. This encourages the moisture expiration occurring in the shade part of the canopy to flow down the southern shaded area from the canopy or adjacent vegetation and to flow across the intervening habitable space. This can be harnessed for positive comfort effects in outdoor living spaces.

The leaves of certain vines and creepers can track the sun during the day, settling to form a closed layer late in the afternoon and at night (Muller 1997). When positioned on a trellis set clear of a wall face, this vegetation forms a daytime shade layer complete with air exhaust paths through and behind the leaf layer. The closed leaf structure forms a night-time insulation air volume layer against the external wall line of the building.

Pergola

(Cooling Inflow)

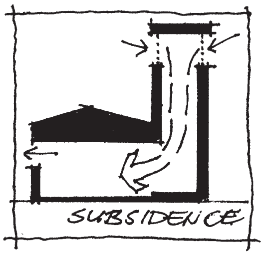


Passive solar design advocates the pergola as a shading device on the northern building side to reduce heat load on the building. The climate responsive approach uses the pergola as a design element on the southern, shade side of the building to enhance the cool characteristics of the air volume there. This cooler air is then available to be drawn into the building during the day.

The air volume under a south-side pergola is humidified by water vapour expiration from the vines and vegetation on and under the pergola, and by water delivered by the vegetation watering system. Air humidification is assisted also by any excess water dripping from hanging basket watering points, or fine spray water delivery to the underside of the vine cover on the pergola roof. Pergola battens can be aligned to winter sun angles to permit continued winter daylight infiltration, but form full shading in summer. For this to work effectively, any vine coverage must be deciduous.

Subsidence Tower

(Cooling Inflow)



In arid lands of the Middle East and Asia, some traditional indigenous architecture embody evaporative air-conditioning systems. The principles applied are to achieve both increased latent heat capacity of air for cooling (increasing the sense of cooling), and air movement from humidification increasing the ambient air mass at the top of a tower (creating airflow downwash within the tower and into the building while drawing in replacement ambient air at the tower top).

This approach was revived in a modern context by the Environmental Research Laboratories at the University of Arizona in Tucson between the mid 1970s and the mid 1980s (Givoni 1994). Temperature drops of up to 11½°C and airflows of about 0.3m/sec are recorded. The system in the US is called a 'cool tower'. The Thompson and Cunningham trial in Phoenix also included windcatcher elements at the top of the tower, and a solar heat chimney exhaust at the other end of the building.

The term 'subsidence tower' is used here to avoid confusion with commercially available air-conditioning systems using a heat exchange bath 'cooling tower'.

A 1990 unbuilt subsidence tower proposal was the Halifax Eco City (Downton 2009). The author trialled locally available filter media in a workshop rig in 1994. Architects Phillips Pilkington incorporated tower elements in the 1997 Monarto Zoological Park Visitor Centre project. Then and later the author constructed tower elements in a number of houses (Prelgauskas 1996).

The tower head comprises wetted pad area (either 'CELdek' – cardboard egg-crate, or 'Woodwool' – aspen shavings). The former surfaces have water flows across, the latter wets the shavings. Water delivery is by low pressure irrigation dripper with rate adjustable outlets.

Rain water is used to avoid suspended solids deposits to pad media. In a minimum water overflow installation, a typical 0.78m² pad is supplied with a 2L/hr water supply. Such low pressure/low flow water delivery is achievable by a DC power diaphragm pump with an integral pressure switch (20psi).

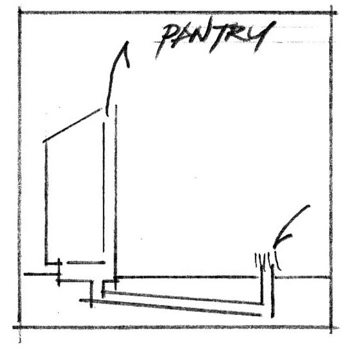
Subsidence tower energy demand is limited to raising water to the filter pad at the tower head.

Specific construction issues to be observed include avoiding perimeter gaps around the pad or unwetted parts of the pad allowing ambient air to bypass the pad. Airflows achieved relate to tower height and filter pad face area (Givoni 1994).

Tower effectiveness is affected by the individual building interior layout, tower position, other climatic building elements, and occupant choices. Installations have succeeded where occupants manipulate the entire building for passive performance. Installation failures include where security precludes night purging, and where not all climate building elements are constructed or are not managed by occupants.

Vented Pantry

(Cooling Inflow)



This pantry form comprises a double carcass pantry interior (including a raised suspended floor), linked to air intake either at floor level with a toe board grille or an earth tube, and top exhaust. The air exhaust is either a thermal flue or clerestory. Air circulates through the suspended floor and wall chimney voids and through floor and ceiling air grilles in the pantry interior which are connected to the air circulation void. The goal of this passive element is to reduce the demand for refrigerator volume by providing alternative passive storage acceptable for whole and bulk foods (Mobbs 1998).

Air inflow via earth tube permits external ingress air to be cooled to near earth temperature (12°C). The tube construction is a pipe which slopes down away from the pantry to allow any condensate to drain out to a gravel sump. An air inlet is located directly above the gravel sump. The cooled air enters the floor void of the pantry and is drawn up the pantry wall void by the passive exhaust forces of stack effect, clerestory or flue suction. A linked adjacent exhaust airflow chimney can utilise the refrigerator coil heat eject air flow to further reinforce pantry ventilation.

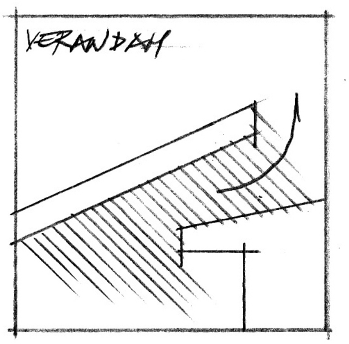
Some air ingress and egress vents are provided from the floor void and the wall chimney respectively into the pantry volume. The air changes remove heat from both the pantry air volume and the adjacent building structure, resulting in temperature stability (about earth temperature) when the pantry is positioned in the building interior.

A reciprocal (warming) approach is the provision of a passive clothes drying cupboard within a building conservatory at the north glazed wall line, via the positioning of an interior floor-level air inlet and an eaves exhaust vent. The higher than ambient temperature and the movement of the air through the air inlet and eaves exhaust allows clothes to dry. This system of drying clothes is particularly useful when outdoor drying is problematic during seasons of persistent wet weather and damp.

Controlling Solar Heat Inflow

Buildings in hot arid climates benefit from building elements which shade the building envelope and structure from direct solar heat. (Approaches not used in Australia so far include roof top ponds with sea water reported by Givoni (1994) for Middle East locations.) The following elements have been integrated with local buildings.

Vented Veranda



Where the sunward facing veranda roof has an air gap to and over the building face, accumulated solar heat load under the veranda roof can vent away. The veranda roof angle results in a larger shade footprint than the traditional veranda fixed to the building eave. Both aspects reduce solar heat load intensity on the building.

Angled Eave

The building element comprises the building external wall angled in relation to the roof eave above. This design element deliberately varies the depth of solar inflow through windows along the room width by differing the shading eave depth along the length of the wall.

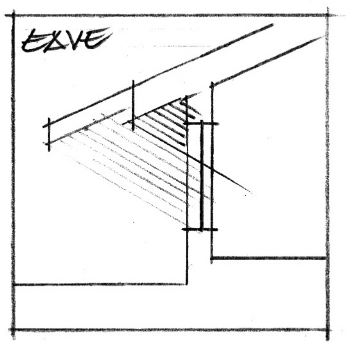
This ground floor conservatory has an angled eave above a glass roof, for enhanced solar control.

Weather does not occur in a steady pattern by season, but varies, with substantial change (e.g. from clear to overcast sky) during a single day or on consecutive days. Passive solar theory and energy efficiency compliance measures in contrast are based on presumed average seasonal conditions.

To provide enhanced occupant control of and access to outlook views, solar inflow and cross ventilation openings, window wall areas are positioned at an angle to the roof eave. The resulting sun penetration to the interior floor varies across the window width, with occupant control able to vary it further.

On days of excess sun, curtains or blinds can be drawn across the window portion with the least eave and greatest sun penetration. The remainder of the window area is already shaded by the larger eave portion. The glazing surface area with open curtain retains unobstructed views and ventilation opening. On overcast days, which can occur in summer, the full opening area is accessible for daylight and cross ventilation.

The result is enhanced control of internal comfort, liveability, and retained passive performance by shading out heat load and retaining daylight and cross ventilation while minimising energy demand.

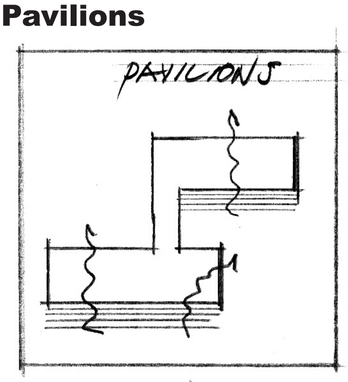


Safari Roof

A safari roof is a roof surface with an open perimeter positioned above the main building roof. The roof directly shades the roof structure below from direct solar heat while allowing the air space between the roof surfaces to vent the heat load upslope and dissipate. This design element represents an increase in effective insulation of the roof structure.

Photovoltaic module arrays on frames mounted to roofs also fulfil this function. The output of monocrystalline silicon panels decreases as their surface temperature rises. Hence power output is improved by airflow in the underside air space.

Pavilions



The performance of passive design elements is enhanced where the building form contains a single room between sun-side airflow exhaust and shade-side air inflow building faces, as there is a minimum obstruction of cross airflow internally.

This approach leads to a building form layout in discrete pavilions which each contain different user zones: family and living spaces in one, private and bedroom in another. The development of user zones within the building also allows for reduced management of the passive systems in areas of less use.

The result is maximised performance of passive elements, reduced management requirements and minimised demand for energy use.

ENERGY EFFICIENCY IN BUILDINGS

Building Code of Australia (BCA) compliance requirements include energy efficiency. Minimum compliance measures are based on thermal flows in materials and construction to traditional passive solar criteria for mechanically air-conditioned housing.

Free-running buildings, in contrast, achieve occupant comfort predominantly by passive and low energy means. An evidentiary folder was developed by the author for post-occupancy measured passive buildings, listing case studies and measured energy use (Prelgauskas 2003). The goal was to provide a basis from which to assess compliance with BCA Alternate Solution. This 'expert judgement' is supported by those measured results.

The assessed compliant baseline house in South Australia (climate zones 4 to 6) might be expected to have an energy use of 22 kWhr/day, whereas free-running houses in SA have been measured to be operating at less than 15 kWhr/day. These include both new building projects and retrofit renovation projects on existing conventional houses. Individual new free-running houses with best practice climate design elements are measured at less than 5 kWhr/day.

Occupant Behaviour

Occupant behaviour in buildings can contribute more to energy efficiency than thermal flow control in materials and construction (Williamson 1988).

Occupant choices include acceptable comfort range, choice of activity level, appropriate clothing, pre-conditioning of spaces (including night purging), and manipulation of passive and active systems to adjust temperature, humidity and air circulation.

The three most effective and mutually reinforcing contributors to reducing energy demand and maximising achieved passive comfort in buildings are integration of the passive systems described above, occupant induction to the building, and provision of an operating manual. The use of mechanical systems can then be a last consideration in securing comfort.

Occupants in buildings with an integrated renewable energy supply are more aware of available energy generation and storage states than occupiers of mains connected buildings. Occupants living in buildings with a renewable energy supply are more likely to adapt their activity and comfort actions to within the available supply without perceiving loss in liveability. In grid-connected buildings the connection between supply and demand is much less direct. Hence energy efficiency management is less evident in both grid-connect only and grid-connect renewable-integrated buildings. Similar awareness and behaviour adjustment also occur where on-site water capture and waste treatment facilities are constructed.

CONCLUSION

In hot arid lands, ambient temperatures, solar heat gain and internal heat loads raise habitable space temperatures beyond human comfort levels. Climate responsive design principles add to those of passive solar design to maximise natural ventilation. No single initiative will be relevant in all applications. However, when deployed appropriately, climate responsive design strategies can make a significant contribution to a designed solution (which will tend visually toward a non-symmetrical disposition).

Finally, it must never be forgotten that the key to the successful operation of most of these systems is occupant behaviour.

REFERENCES

Cunningham, WA and Thompson, TL, 1986, 'Passive cooling with natural draft cooling towers in combination with solar chimneys', in *Proceedings of PLEA Conference*, Pecs Hungary

Downton, PF, Prelgauskas, E and Hancy, M, 1991, 'Climate Responsive Building Design in the South Australian Context', *SA Energy Forum*

Downton, PF, 2009, *Ecopolis: cities and architecture for a changing climate*, Springer

Givoni, B, 1994, *Passive and Low Energy Cooling of Buildings*, Van Nostrand Reinhold, New York

Gray, T, 2002, *Earth Garden Green House Plans Book*

Kessler, HJ, Yoklic, MR and Medlin, RL, 1994, 'Community concepts for living in arid regions – a solar oasis' in *Proceedings of International Passive and Low Energy Architecture Conference*, Mexico City

Mobbs, M, 1998, 'The Refrigerator', Chapter 10, *Sustainable House*, ed. 1, Choice Books, Sydney

Muller, CF, (ed) 1997, 'Leitfaden zum oekologisch orientieren Bauen', Environment Dept, Berlin p73–83.

Practice Note, *Architect SA*, Spring 2001, p26

Practice Note, *Architect SA*, Autumn 1997, p16

Prelgauskas, E, 2003, *Performance Outcomes – Free Running Buildings Achieving Energy Efficiency*, F.McD Technical Library.

Prelgauskas, E, 1996, www.emilis.sa.on.net

Williamson, T, Coldicutt S et al, 1988, *Thermal Comfort and Preferences in Housing: South & Central Australia*, University of Adelaide, South Australia