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Solar passive buildings for developing countries

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Abstract. This paper is meant to be an indicative survey of developments in solar passive building technology relevant to developing countries. The evolution of this area during the last fifty years is reported along with the scientific principles and design concepts underlying these developments. Factors to be considered for design strategies such as direct gain, isolated gain, indirect gain and roof evaporative systems are then described. Rating parameters for assessing the performance and benefit and cost parameters are then outlined. Successful examples illustrating each of the design concepts, mainly from Indian buildings constructed during the last fifteen years, are then detailed along with their performance based on actual monitoring, if available. Concluding remarks indicate the current and future trends. A survey is made of papers marking significant milestones in the development of solar passive building technology relevant to developing countries.

Keywords. Solar passive; solar heating; solar cooling; energy conservation; renewable energy; solar architecture

1. Introduction

Amongst all the solar technologies available, solar passive buildings are perhaps the most environmentally compatible, resource-wise and economically sustainable, and immediately humanly available in terms of skills and methods of construction. Their contextual relevance to industrialized countries is, however, different from that to developing ones. For the former group, where space heating and cooling is the accepted practice, they are primarily employed and rated for fuel substitution, whereas in the developing countries, they only reduce the degree of discomfort and constitute a low-energy approach for normally non-conditioned buildings. Developing countries, being in tropical climates, preferably require cooling, whose economics cannot be so well substantiated in the absence of any alternatively used fuel-consuming machines. The economics can be easily ascertained, however, for heating in the cooler months or at hilly locations of developing countries, because of the cash value of saving fuels, and that is why passively heated buildings are finding acceptance in such regions.

Since solar passive buildings are the culmination of an evolutionary growth of architecture, consciously during the last fifty years, we define their exact scope and trace their historical evolution during this period (§ 2) before outlining the basic scientific principles and design concepts (§ 3). We then briefly discuss the design analysis and optimisation aspects both for heating and cooling by passive means (§ 4) and follow-up with rating parameters (§ 5). Some landmark buildings, mainly from India, are cited as examples of successful design in § 6, while economic aspects are discussed in § 7. This concise review is meant not as an exhaustive essay but as an indicative survey to bring home the relevance of this approach for developing countries.

2. Scope and historical evolution

2.1 *Scope*

In the broad area of energy conscious design, we define the various phases of growth as follows.

(i) Solar architecture uses/excludes solar radiation with the help of devices – mechanical, such as evaporative cooling, or architectural, like passive integrated water heaters or sun control louvers.
(ii) Energy-conserving buildings primarily use low-energy materials and reduce possible consumption by proper choice of orientation, urban design, landscaping and building envelope parameters.
(iii) Passive buildings, even though using some or all of the above, are primarily those which use the temperature difference caused by the sun/wind as the driving potential via natural processes such as convection, evaporation, radiation and conduction to collect, store and distribute or reject energy into internal spaces. Some of the design features are glass-walled rooms, chimneys, fenestration for natural daylight and heat, ponds or water sprays for evaporative and radiant cooling/heating.

2.2 *Historical evolution*

The three streams defined in § 2·1 and the evolution of heating, ventilating and air-conditioning (HVAC) equipment in parallel constitute the four threads which have been used to weave the pattern of energy-conscious architecture during the last fifty years.

2.2a *Bioclimatic period (1936–65)*: During this period, most of the architect-designed buildings were supported by some kind of thermal analysis with regard to climate and materials apart from the geometry of buildings *vis-a-vis* solar geometry. This was the period during which the Bauhaus movement headed by Gropius and mechanical aesthetics propounded by Le Corbusier had their sway. In the meantime, mass-produced modular heating, ventilating and airconditioning equipment displaced custom-designed HVAC systems. Architecturally, bioclimatic design methodology marked the peak of this period (Olgay & Olgay 1963).

2.2b *Integrated designs – early phase (1940–70)*: Full size solar houses were built as models, mainly by engineers. The architects relegated the passive design in favour of reliable HVAC systems or active solar buildings, since fuel was inexpensive and easily available. Analysis rather than creative synthesis was the essence of this period, which laid the foundations for energy-conscious architecture. Notable buildings during these periods were the following.

Bioclimatic approach

- Golconde, Pondicherry, India (1936–40) – Raymond, Nakashima and Sammers.
- India International Centre, New Delhi, India (1957) – Joseph Stein.
- St. Georges School, Liverpool, England (1961) – Morgan.

Solar active approach

- MIT Solar Houses, Cambridge, USA (1939–1958) – Anderson and Hottel.
- Lof House, Denver, USA (1958) – George Lof.
- Kapur Solar Farm, New Delhi, India (1963) – J C Kapur.

2.2c *Sun fuels for preheating (1970–83)*: This was the era of retrofits, controls and system design, so as to derive the maximum contribution from the sun, subject to cost constraints. Energy consciousness 'leaped' over houses to include public buildings like schools, market places and hospitals. Problems of legal solar access rights and life cycle costing for economic justification came to the fore. India missed the scene, but demonstration programs of EEC in Europe and DOE and NSF in USA practically changed the course of building construction and architectural design practice. Operating and maintenance problems of retrofit mechanical devices became important. Building energy rating parameters were developed and used. A comprehensive survey of solar houses in Europe is included in Palz & Steemers (1981).

2.2d *Solar passive buildings (1970–)*: This is the period when a new solar-architectural ethic was first defined and practised. Buildings became primary elements for collection, storage and distribution of energy within the buildings and 'solar' became a symbol of quality rather than cost reduction. Daylighting, resource conservation, vegetation and envelope design including insulation became the keywords. Solar communities were born and superinsulated houses and earth-sheltered buildings (in the modern context) made their appearance. Notable buildings of this phase are as below:

- Zome House, Albuquerque, USA (1971) – Steve Baer.
- Trombe House, Pyrenes, France (1972) – Felix Trombe and Mitchell.
- Sky-therm House, Arizona, USA (1973) – H R Hay.
- Ecohouse, Auroville, India (1976) – C L Gupta, Vikas and R Gupta.
- Balcomb House, Arizona, USA (1979) – Susan and Nichols.
- SOS Children's Village, Leh, India (1980) – C L Gupta and V Lahiri.
- Sangath, Ahmedabad, India (1986) – B V Doshi.
- Vidyadhar Nagar, Jaipur, India (1980) – B V Doshi and Associates.

2.2e *Current developments (1980–)*: New building energy products such as phase-change material (PCM) tiles, heat selective films for windows, solar cladding panels, thermal diodes, variable insulation cavity walls and new kinds of blinds have been developed and are now commercially available. Computer-aided design (CAD) programs for design including solar thermal analysis and simulation and operating programs for building systems management are now routinely available. Attempts have also been made at optimisation in terms of minimum overall costs or maximum energy conservation or minimum degree of discomfort. On-site waste recycling systems using high rate reactors for biomethanation are under field trials. On-site power systems have been developed and are being field tested. Watson (1981), Givoni (1983), Cook (1983) and Balcomb (1987) have summarised these developments in their recent presentations at the International Solar Energy Society (ISES) congresses and passive and low-energy architecture (PLEA) meetings. Authoritative manuals and text books are available on science and design of solar passive buildings, e.g. Lebens (1979), Balcomb (1982), Sodha *et al* (1986, pp. 238–42), Cook (1990) and Prakash (1990). Earlier texts on climatic aspects of design, e.g. Givoni (1976) and Koenisberger *et al* (1975) contain highly relevant background material.

3. Basic design concepts and scientific principles

3.1 *Basic design concepts*

In solar passive buildings, there are no solar collector panels; parts of the building collect, store and distribute solar energy. A schematic sketch shows their interrelationships (figure 1). South-facing glass windows, greenhouses, glass cladding on walls or skylights serve as collectors, while floors and walls provide thermal storage mass to hold heat till it is needed for sundown hours or when the ambient starts to cool. Properly placed vents, windows, skylights or shading glass surfaces prevent overheating during summer or on very sunny days in cold weather. Depending upon the elements used, we have the following for solar heating.

3.1a *Direct gain system*: This works with radiant inputs directly into the indoor space, mainly absorbed by the floor mass.

3.1b *Isolated gain system*: This has an attached sunspace to provide a hotter ambient and thereby reduce losses and partly convect heat through connecting doors and windows by natural convection.

3.1c *Indirect gain system*: This system has a glazed masonry sun-facing wall (southern in the northern hemisphere) with intervening space for air flow. This may be vented to have a Trombe wall in which heat is transferred indoors by natural convection during the day and by time-lag of conducted heat by the evening and night.

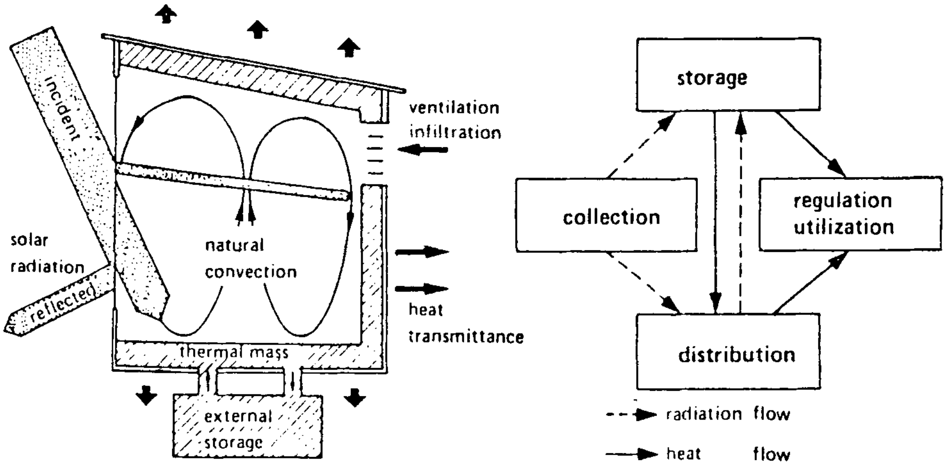

Figure 1. Solar passive building – basic concept.

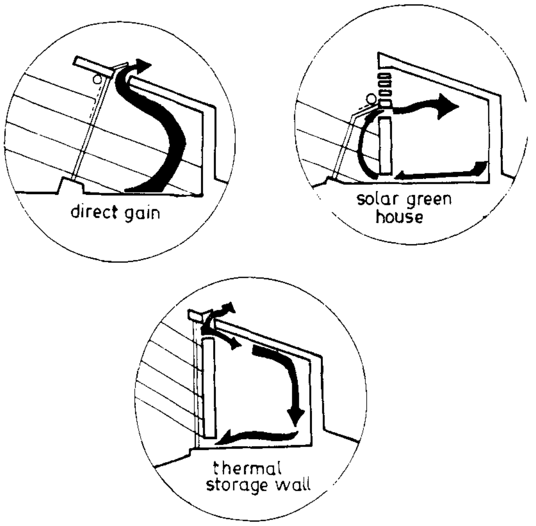

Figure 2. Schematic of solar passive heating systems.

3.1d *Roof water systems*: These are used for heating and cooling in terms of 10 cm deep ponds of water on the terrace coupled to insulated mobile shades or else for cooling alone when a water spray is coupled to water-retaining fabric attached to the roof deck.

Details of these systems, relevant to architects, are given by Gupta *et al* (1990) and the underlying physics is discussed by Heidt (1983). Schematics of heating systems are shown in figure 2. Details of a solar Trombe wall, the most popular solar passive element, as applied to the design of schools in the Ladakh region are given in figure 3,

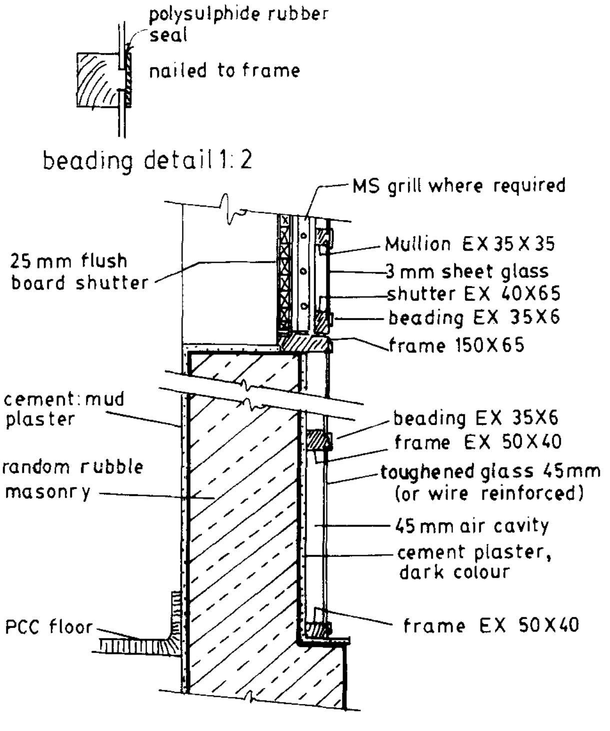

Figure 3. Trombe wall – specifications for a school (Ladakh).

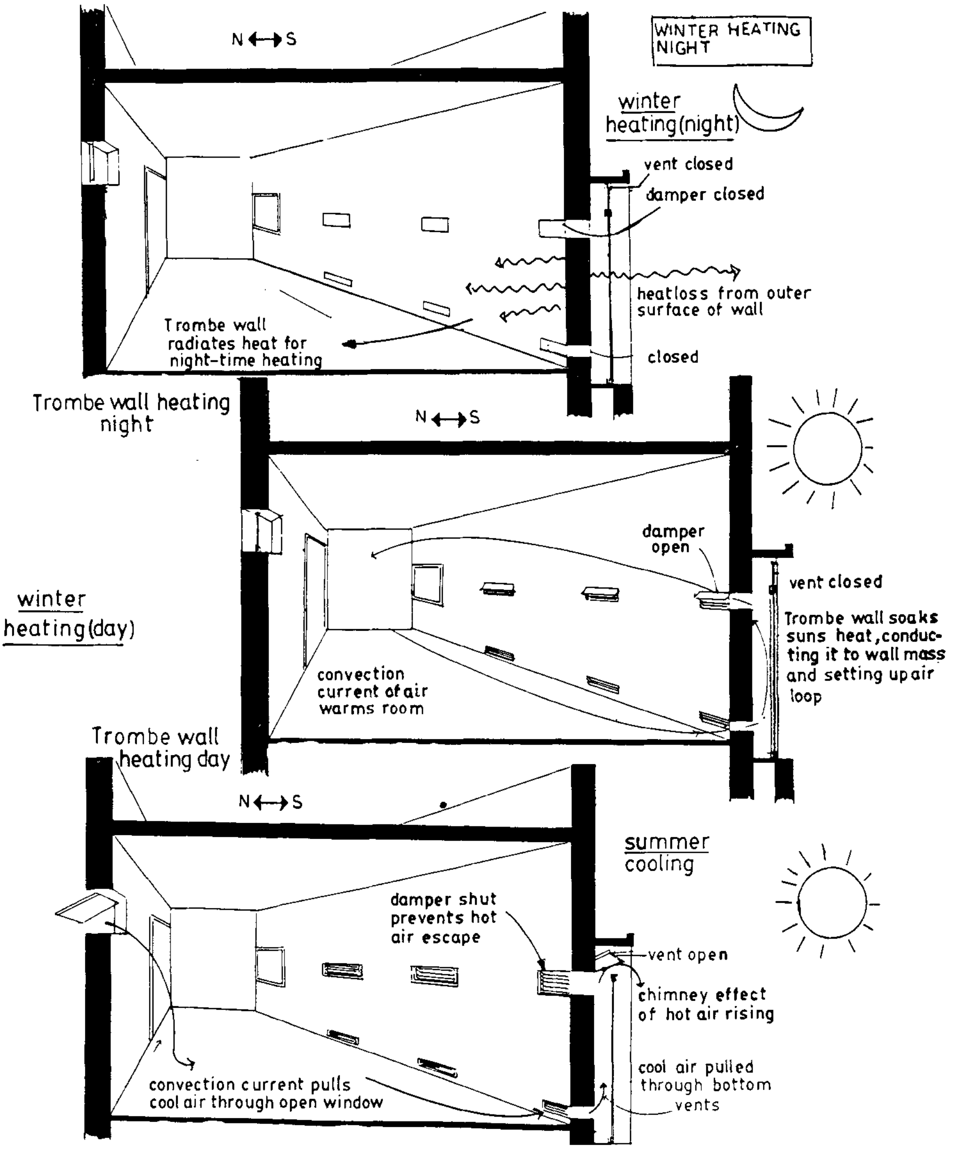

Figure 4. Trombe wall – working principle.

and its working principle is depicted in figure 4. A good overview is given by Balcomb (1979).

3.2 *Scientific principles*

Buildings are normally treated as a grouping of rooms with the roof, walling and floor elements of each room in parallel. One-dimensional heat flow governed by a conduction equation in layered structures is considered, each layer having constant thermal properties without internal heat generation. These elements can be treated as lumped resistance–capacitance (*RC*) networks or as quadripoles. Boundary conditions are usually of the third kind (radiative) with evaporative terms in case of roof sprays and ponds, and nonlinear radiative cooling to sky for exposed horizontal elements. Floors are assumed to have constant temperature at the depth of the water table equal to the annual ambient dry bulb temperature of the place. Steady periodic methods are usually employed with hourly variation. The simulation cycles vary from one-day every month to nine-days every season. In case the effect of wind is to be taken into account in changing the surface heat transfer coefficient on the external facade, numerical methods with *RC* networks are employed rather than matrix or admittance or response procedures, which necessitate constancy of the network. Single rooms are treated with the wall of adjoining rooms as adiabatic partition walls or zoning is resorted to with the corresponding complication of having to solve sets of simultaneous equations. Either variable temperatures for non-conditioned buildings and buildings with partial energy inputs or airconditioning loads for controlled indoor temperatures can be determined. A comprehensive survey of the methods required for thermal analysis of buildings (Gupta *et al* 1970), and, more recently, for solar buildings (Balcomb 1987) are now available. The main attempts from 1970 to 1990 have been to computerize these methods for mainframe and, more recently, desktop computers. A typical room thermal circuit (for the southern hemisphere) according to Yamaguchi (1983) is shown in figure 5.

A pertinent consideration that distinguishes the analysis of solar passive buildings from the thermal analysis of normal buildings is the definitive need to consider internal radiative-convective exchanges as delta rather than star networks. This was first attempted by Buchberg *et al* (1964) using the *RC* network and numerical methods, by Gupta (1964) using quadripoles and steady periodic methods, and by Raychaudhuri (1965) using equivalent time constant sections and transient response methods. Recently, such techniques have been used by Subba Rao & Anderson (1982) and Yamaguchi (1983) for solar passive buildings. This approach definitively proved that

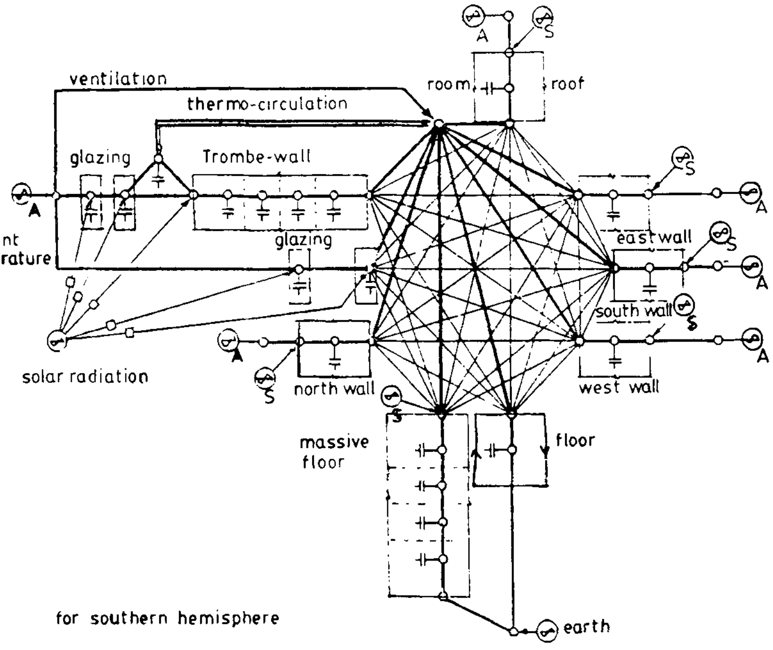

Figure 5. Thermal circuit of a room.

the time-lag of individual building elements is invalid for unconditioned buildings as a whole. At that time, however, it was considered only a refinement in the analysis. For solar passive buildings, where internal storage acts as an essential buffer between collection and distribution, particularly for a larger radiant fraction of heat inputs, simulation of internal temperature swings cannot be properly estimated without this coupling. Approximate methods are being continually evolved to make these concepts available for use in architectural practice (e.g. Balcomb 1981, 1983). Another recent simplification has been to treat solar inputs as invariant with respect to orientation, similar to air temperature but with varying incidental area of the building as a whole determined by projective methods (e.g. Kim 1983, Huang 1986, pp. 122–7, and Gupta & Raghavan, unpublished work). Optimisation methods have also been coupled to these simulation tools to determine optimal values of insulation, orientation, aspect ratio etc. for minimum energy consumption for thermal tempering, e.g. by Gupta & Spencer (1970), Gupta & Ram Mohan (1981), to determine the optimum combination for cost minimisation by Gupta & Anson (1972) and for hybridising of direct gain and Trombe wall systems by Yamaguchi (1983) and Sodha *et al* (1989, pp. 238–42). Statistical variation of daily inputs over monthly periods have also been incorporated using the unutilizability approach for direct gain and Trombe wall systems by Monsen *et al* (1981, 1982). These are now being extended to cover the sequencing of days with help of second order statistical analyses e.g. Gordon & Reddy (1989).

4. Design guidelines

Amongst the design guidelines available, three are for heating, one is for heating and cooling, and one is for cooling only. Each of the systems in these categories has specific design limitations and use. Hence, the designer has to choose the one that satisfies the majority of criteria set for a particular building on a given site and the availability of space as well as the fineness of thermal regulation required. The following guidelines can be of help at the initial design stage. These are mainly compiled by Gupta *et al* (1990).

4.1 *Solar passive heating*

4.1a *Direct gain (increased fenestration i.e. glass area): building form* – The building is usually oriented along the east–west axis, with spaces needing heat located along the south wall.

Glazing – The major glass area must be oriented towards the south and it is essential that windows be carefully designed to eliminate the problem of glare often associated with direct gain systems.

Material – The system generally implies a heavy building with the interior wall and floors constructed of masonry materials.

Thermal control – Direct gain systems are characterised by daily indoor fluctuations. To prevent overheating, shading devices are used to reduce solar gain, or excess heat is vented out by opening windows/vents.

Retrofitting – Retrofitting an existing building with a direct gain system is somewhat difficult, since the building by itself is the system.

The system demands skilful and total integration of all architectural elements within each space: windows, walls, floor, roof and interior surface finishes. A direct gain system can usually be built for the same cost as a conventional masonry system.

4.1b *Isolated gain (attached greenhouse): building form* – The greenhouse must extend along the south face of the building adjoining the spaces to be heated.

Glazing – To heat one square metre of building floor area (excluding the greenhouse) approximately 75% of greenhouse glass area is required in normal constructions.

Materials – The major construction material in the greenhouse is double glass or transparant plastic and there is a common wall (thermal mass masonry or water) between greenhouse and building.

Thermal control – Temperature in adjoining spaces is similar to temperatures in thermal wall storage systems.

Retrofitting – Retrofitting can be carried out easily by adding a sunspace to an existing building on its south side in the northern hemisphere. A useful feature of the system is that it can produce fresh vegetables, apart from the capacity to heat itself and space adjoining it.

4.1c *Indirect gain – (glazed storage wall)*: This can be a vented cavity – Trombe wall – or an unvented cavity.

Building form – The depth of a space is limited to approximately 5 or 6 metres, since this is considered the maximum distance for effective radiant heating from a solar wall.

Glazing – The south-facing glass functions only as a collecting surface and admits no natural light into the space except through windows, which may be allowed.

Materials – Either water or masonry or built-in PCM modules can be used for a thermal-mass wall. Double glazing in front of the wall is considered desirable unless insulating shutters are applied over the glazing at night.

Thermal control – Indoor temperature fluctuations are controlled by wall thickness. The heat output of a masonry wall can be regulated by the addition of thermo-circulation vents with openable dampers or by movable insulating panels or drapes placed over the inside face of the wall.

System efficiency – For the same area of wall and heat storage capacity, a water wall will be slightly more efficient than a masonry wall.

Retrofitting – This system can be added without much difficulty to the south wall of a building.

The system allows for a wide choice of construction materials (exclusive of the thermal wall) and interior finishes, and offers a high degree of control over the indoor thermal environment.

4.2 *Heating and cooling*

4.2a *Roof-top shallow solar pond*: It acts like a panel radiant heater/cooler and is primarily meant only for one-storey buildings with thin horizontal roofs. It is also ineffective during monsoons and roofs need special care with regard to weather proofing.

Building form – Since the roof itself is a collector, this system is most suitable for heating or cooling one-storey buildings, or the top floor of a multi-storeyed structure.

Glazing – For summer cooling, the pond must be exposed to as much of the night sky as possible.

Materials – Roof ponds are generally 10–20 cm in depth. A structural RCC grid system or metal deck, which also acts as a finished ceiling and radiating surface, is the most commonly used support for the pond itself.

Thermal control – Roof-pond heating and cooling is characterised by stable indoor temperatures and high levels of comfort due to the large area of radiative surface.

System efficiency – Roof ponds, which are lined with plastic and have movable insulation, range in efficiency from 30 to 45%. It should be noted that the effectiveness of the seal made by the movable insulation will have an impact on the efficiency of the system.

Retrofitting – The requirements of a large area of radiating surface plus structural and modular considerations make it difficult to apply to existing structures.

Solar roof ponds are an inexpensive and effective method of providing both heating and cooling in dry climates with clear night skies.

4.3 *Solar passive cooling*

4.3a *Roof spray on an absorbent fabric*: This system was invented by the Central Building Research Institute (CBRI) (see, for example Jain & Rao 1974). The roof acts like a panel radiant cooler. It was primarily designed for one-storey buildings with thin horizontal roofs but was later extended to normal masonry roofs and multi-storey buildings (e.g. Jain 1989). The principle is to maximize the effective cooling efficiency of the roof deck by making water evaporate in as close a thermal contact with it as possible during the day, and using, in addition, radiant cooling to the sky during the night.

Building form – No restriction except suitable weather proofing without appreciable increase in thermal resistance or capacity.

Glazing – With unobstructed exposure to the night sky, it is ideal for hot, dry climates with clear night skies.

Materials – Gunny bags/coir matting are used in close thermal contact with the roof. A spray of water from sprinklers or wicks in a perforated pipe is obtained to just wet the surface. The roof fabric is necessary to increase the specific surface of evaporation and obtain a thin layer of water so as to need spraying only three to four times in a full day.

Thermal control – An electrical conducting sensor can operate a relay to shut a solenoid valve or open it for gravity flow. Only a few watts of DC provided by the photo-voltaic (PV) panel is sufficient to automate the system. Usually the water spray is needed at the rate of 10 litres per square metre per day (24 h).

Efficiency – An indoor air temperature depression of upto 8°C has been observed in favourable climates with complete extinction of vertical temperature gradients and asymmetric radiation from the ceiling.

Retrofitting – Commonly used for factory roofs after checking for weather proofing.

The system is very effective in terms of cooling per unit investment and needs very low running costs.

4.3b *Terrace garden with spray of water*: This is a variation of the system in § 4·3a with significant increase in dead weight, thermal capacity and resistance. It is highly effective during day and needs lesser water; one can have a terrace lawn for use.

4.3c *Earth sheltered buildings*: Underground construction also provides excellent cooling potential. The temperature of the ground at some depth remains almost stable throughout the year, and depending on latitude, stays at approximately annual average dry-bulb-temperature (DBT). In climates with severe summer or winter temperatures or both, underground construction provides considerably improved 'outside' design temperatures, to remove much of the demand from the heating system, and all the demand from the cooling system. Two words of caution in underground systems: First, humidity and moisture conditions which result from below-grade construction may greatly influence living comfort in the already humid regions and second, underground buildings cannot take maximum advantage of comfortable outside temperatures, but instead have constant exposure to the cooler ground temperature.

4.3d *Induced ventilation*: This solar passive cooling system makes use of sunshine for inducing air movement to augment natural ventilation for building comfort. By using the sun to heat air in one restricted area, with a location somewhat lower than the adjacent non-solar-heated areas, a temperature difference is set up, causing natural air movements, in which hot air rises. The pocket of hot air created inside at temperatures greater than the ambient, vents to the outside, drawing replacement air from the living spaces. The living spaces in turn draw replacement air from the coolest outdoor air source, usually near planted north areas. Thus, a "thermal chimney" can, by use of solar energy, cause continuous air circulation through a building to provide solar passive cooling.

5. Rating parameters

As mentioned in § 1, the rating procedure for unconditioned buildings, when designed as solar passive or retrofitted with solar passive features, has to be different from that of normally conditioned buildings. There are many methods, but those better known and logical/simpler to use are presented below. A good critique of these is available (see for instance, Clausing & Drolen 1979).

5.1 *Degree of discomfort method*

This is a method based on predicted/measured hourly internal air (DBT) temperatures wherein discomfort degree hours are calculated for day and night times outside the comfort zone and normalized for time period length by dividing by total degree hours within the comfort zone (Gupta *et al* 1970). No distinction is made between lesser peaks for longer hours or higher peaks for an hour or two. Also, a linear scale is considered even though physiological responses to environmental stimulii are logarithmic and not linear. We define degree of discomfort as

$$D = \frac{1}{N}\left\{\sum_{\text{day}}\left[\frac{|t_{\text{ia}} - t_{\text{c}}|}{\Delta D} - 1\right]^{+} + \sum_{\text{night}}\left[\frac{(t_{\text{ia}} - t_{\text{uN}})^{+}}{\Delta N}\right]\right\},$$

where

D = degree of discomfort;
N = number of ordinates considered in design cycle;
t_{ia} = temperature of internal area or space (°C) – measured or computed;
t_c = day-time preferred temperature for comfort (°C);
t_{uN} = upper limit for night-time comfort (°C);
ΔD = deviation allowed in the day = half the range of comfort zone (°C);
ΔN = deviation allowed in the night for comfort (°C);
$+$ = only positive values to be considered, negative values to be neglected.

Temperatures and comfort parameters can also be environmental temperatures or tropical summer index (BIS 1988).

5.2 *Solar load ratio method*

This is an empirical method developed by the Los Alamos Science Laboratory Group over a period of years for various kinds of solar passive buildings. Monthly estimates of solar heat fraction (SHF) are made, which yield an annual SHF within $+2{\cdot}5\%$ of the value based on hourly calculations, by correlating SHF with solar load ratio (SLR), which is:

$$\text{SLR} = \frac{\text{radiant energy (solar) absorbed by the building}}{\text{monthly heating load}},$$

where

$$\text{monthly heating load} = \text{global loss coefficient of the building} \times \text{floor area} \times \text{monthly degree hours},$$

and

$$\text{SHF} = a_1 \times \text{SLR};\ \text{SLR} < R$$

$$= a_2 - a_3 \exp(-a_4 \cdot \text{SLR});\ \text{SLR} > R.$$

These expressions do not vary with location. The values of the constants a_1, a_2, a_3, a_4 and of R, however, are different for different types of passive systems. These have been derived with reference to baseline building specifications for an internal building temperature of 18·3°C with dumping beyond 23·9°C. A 2·7°C equivalent contribution by internal loads is to be accounted for by the base temperature required for calculation of degree hours in USA.

$$\text{System efficiency} = \frac{\text{SHF} \times \text{building load}}{\text{incident radiation on solar wall}}.$$

5.3 *Solar heat effectiveness* (*SHE*) *method*

The solar load ratio method does not allow a comparison or integration of solar passive strategies with conservation strategies, e.g. enhanced insulation, as it is computed with respect to ambient conditions. In the case of the SHE method, the base line reference is with respect to indoor temperatures of the unheated building (not the ambient) and it is defined as

$$\text{SHE} = \frac{\begin{array}{c}\text{heat equivalent of the temperature elevation of a solar room}\\ \text{above that of an untreated room}\end{array}}{\begin{array}{c}\text{heat required by the solar room to reach comfort}\\ \text{temperature (say, 18·3°C)}\end{array}}.$$

It is a measure of the fractional discomfort removed for a given type of building and treatment. This has been used by Gupta & Prema (1983).

5.4 *A low-cost field method*

This method utilises the daily maximum and minimum temperature values for indoor and outdoor environments over a heating season to estimate the decrement ratio and average temperature elevation of the indoor above the outdoor. For ordinary buildings, it had been developed by Drysdale (1952) and has been used by B Stickney (private communication) for solar passive buildings.

$$\text{Decrement ratio } \lambda = \frac{\text{indoor air temperature swing}}{\text{outdoor air temperature swing}},$$

where

$$\text{temperature swing} = (T_{\max} - T_{\min}),$$
$$\text{average temperature elevation } (\Delta T) = (\text{indoor mean temperature} - \text{out-door mean temperature}),$$
$$\text{mean temperature} = 0{\cdot}5\,(T_{\max} + T_{\min})$$

Day and night ΔT's can also be derived from differences of maxima and minima respectively. Low to moderate values of λ and moderate to high values of ΔT indicate good performance. Solar passive buildings invariably have indoor temperature fluctuations. Temperatures between 22 and 28°C may be considered comfortable for human occupancy and between 10 and 35°C are allowable for plants in attached sunspaces for tropical climates. These limits are adjustable for humidity and movement of indoor air (using fans) by using TSI limits prescribed by the Bureau of Indian Standards (BIS) (1988).

6. Case studies

A few selected case studies from India on solar passive systems are being reported with performance data, wherever available, to illustrate various types of systems enumerated. More complete accounts are available in Gupta (1987) and with A Duggal (1983, unpublished).

6.1 SOS *Tibetan Children's Village, Choglamsar, Leh – sunspace*

An attached greenhouse, with a movable internal shade for the ceiling and closable vents for the south-facing glass wall of the common space, and double-glazed, solid masonry wall with a vent system for two end-rooms have been retrofitted to the SOS Tibetan Children's Village dormitory in Choglamsar (Gupta & Prema 1983); the plan and section are shown in figure 6. The climate is severe with annual heating

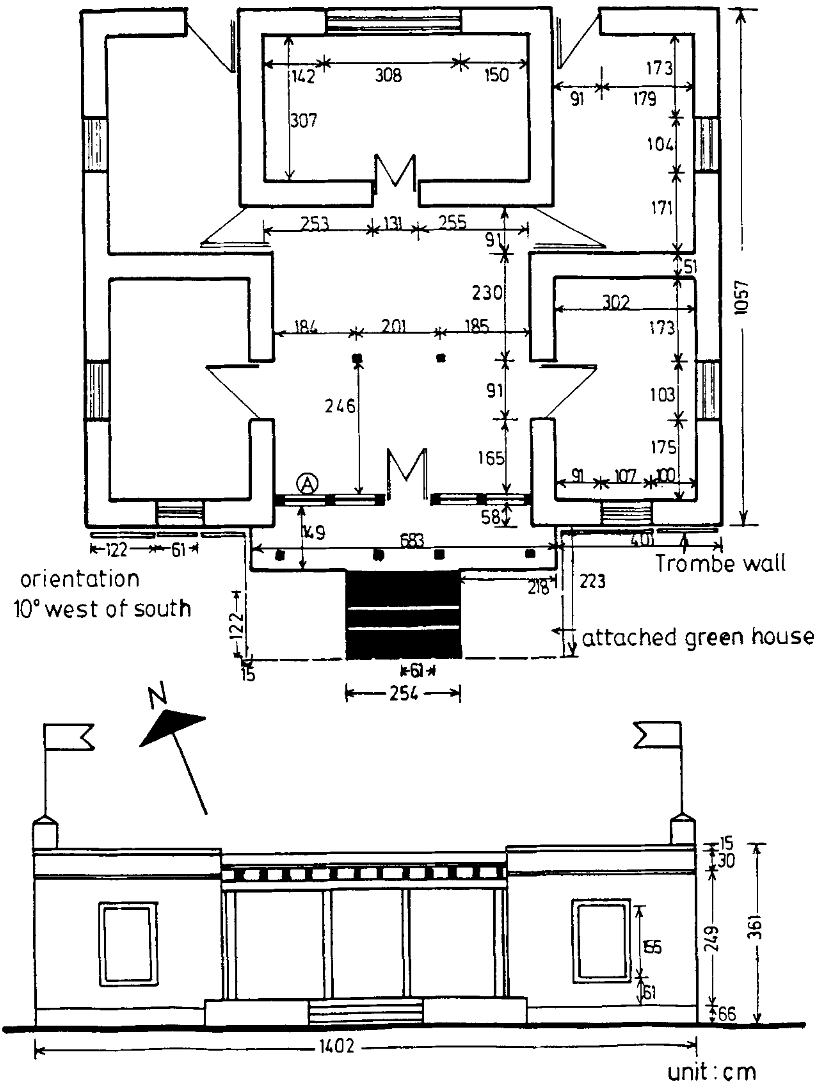

Figure 6. SOS village dormitory systems.

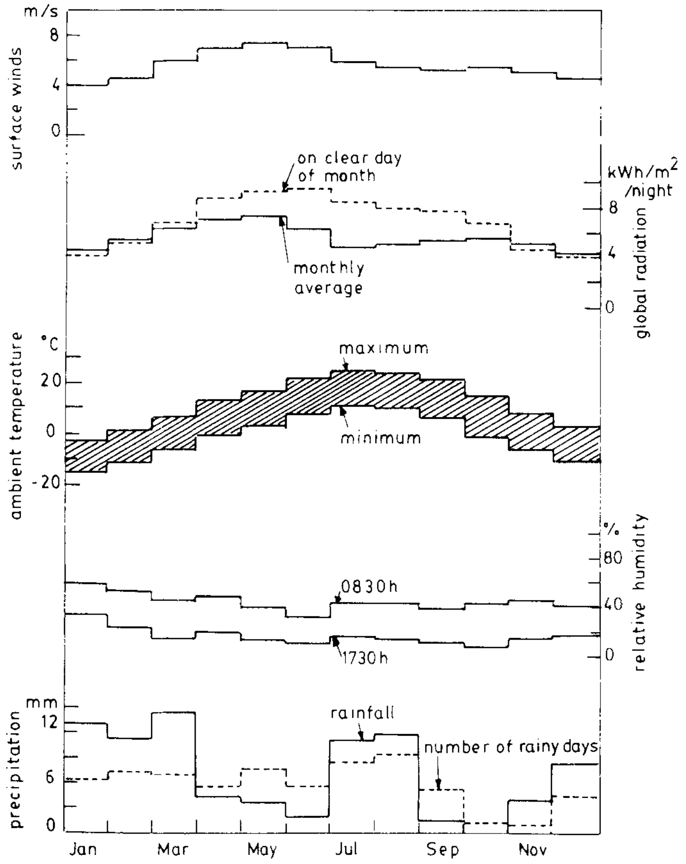

Figure 7. Typical climatic data required (Leh).

degree days equal to 4400 and annual sunshine hours exceeding 2900, see figure 7 for climatic data (Prakash *et al* 1988). In this austere and yet beautiful building amidst snowy mountains, traditional construction materials, namely, mud, timber and glass, had been used in the traditional style – solid adobe walls, 0·53 m thick (external) and 0·38 m thick (partitions), heatloss coefficients (U) values of 1·64 and 1·76 $\mathrm{W\,m^{-2}deg\,C^{-1}}$, respectively, and a wooden roof with mud topping (U value = 2·44 $\mathrm{W\,m^{-2}deg\,C^{-1}}$). The floor was wooden decking over a crawl space, which should normally have been used for heating in traditional Tibetan style but was not used for economic reasons. The extended floor in greenhouse space was solid masonry and provided good thermal storage mass of 1·44 $\mathrm{MJ/m^2K}$. Attached greenhouse and Trombe wall retrofit data are given in table 1. Table 2 gives measured temperature data, namely the maxima and minima for the Trombe room, greenhouse space and ambient climate. A typical day profile is also shown in figure 8. The temperature of the greenhouse space follows the solar Trombe wall room very closely during day but is much cooler at night in spite of shading the ceiling from night sky cooling. This is because the vertical walls are single-glazed and are not provided with shades and there are howling cold winds rushing through the Indus Valley parallel to these houses. This building has changed the building style in nearby villages almost without any conscious technology transfer on the part of the technical team. All the 20 dormitories have been retrofitted in this

Table 1. (a) Building specifications – (SOS Tibetan children's village).

Element	Materials	Thickness (m)	Mass (kg m^{-2})	U-value (Wm^{-2}K^{-1})
Walls				
External	Sun-dried mud bricks	0·53	1053	1·64
partition	Sun-dried mud bricks			
	North wall	0·38	755	1·76
	East wall	0·53	1053	1·47
Roof	Mud on wooden deck	0·20^{+}		
		0·03	477	2·44
Floor	Wooden deck on ground	0·03^{+}		
		0·27	596	—

b

Element	Trombe room	Common room
Floor area (m^2)	13·6	59·4
South facade (m^2)	9·5	17·3
Glass cladding (m^2)	9·5	41·3
Glass area/floor area	0·68	0·69
Frame shadow fraction	0·16	0·08

pattern by the SOS village and many householders nearby have used the system in their houses, using locally available skills and materials.

6.2 *Hotel Tsemo-La, Leh (34°N) – Trombe wall*

Under an Intermediate Technology Development Group–Tata Energy Research Institute (ITDG–TERI) project, a Trombe-wall heating system was designed and a second-storey room built in Hotel Tsemo-La (previously Karakoram Hotel) incorporating this design along with cavity walls in Leh, Ladakh, during 1978 (34°N at an elevation of 3500 m) (Norberg 1980; Stambolis *et al* 1980). The solar room has a floor area of 30 m^2 and the solar wall-to-floor area ratio is 0·635.

Table 2. Monthly mean measured temperature – (SOS Tibetan children's village).

	Maximum temperature (°C)					Minimum temperature (°C)				
	Trombe		Greenhouse			Trombe		Greenhouse		
Month	Solar	Control	Solar	Control	Shade	Solar	Control	Solar	Control	Shade
(1980)										
September	32·2	27·0	29·6	26·2	17·4	20·0	16·6	17·6	14·5	6·3
October	29·4	20·7	25·6	—	11·6	16·2	11·4	13·4	—	1·2
November	21·8	13·7	20·5	—	7·1	11·6	5·9	5·8	—	– 5·6
December	21·6	10·2	17·0	—	2·8	6·8	2·4	4·6	—	– 9·4
(1981)										
April	24·0	19·0	24·8	—	11·6	17·0	14·0	15·0	—	– 1·6
May	25·8	23·6	25·2	22·2	16·6	21·0	19·0	19·0	17·0	3·2
June	27·8	26·8	29·4	25·0	19·6	21·0	20·4	21·0	20·0	7·0
July	31·1	29·2	31·8	28·6	25·0	25·4	23·6	24·0	23·0	12·8

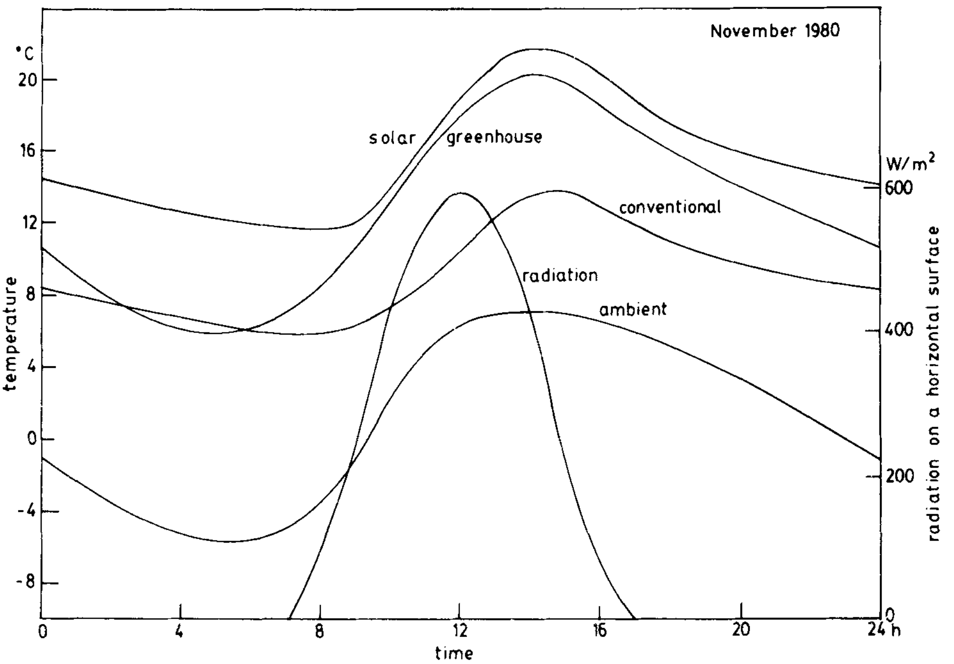

Figure 8. SOS village – typical daily temperature profiles.

Since only mud, timber and glass were available at the site – the latter for making sun rooms known as *Shalkhangs* – only these were used in the construction. Cavity walls of 37·5 cm thickness using two 15 cm thick layers of dried adobe blocks with polythene bags filled with straw as cavity insulation (wall $R = 0{\cdot}858\,^{\circ}\mathrm{C\,m^{-2}\,W^{-1}}$) and a wooden deck roof, with mud insulation on the top (with a slight slope) and straw-filled purlin space with wood-veneer lining below acting as the ceiling ($R = 1{\cdot}648$), were the main building elements. The south wall with two slit windows was double glazed and vented to act as the Trombe wall. This room has been monitored by using mercury in glass thermometers with an accuracy of 0·5°C installed in mid air at 1·2 m from the ground both in the solar room and in a conventional one, vide Gupta (1980, unpublished) and Gupta & Ram Mohan (1981). Data were

Table 3. Thermal preformance data for solar room, Leh. (Hotel Tsemo-La).

	Maximum temperature (°C) (Shade DBT)			Minimum temperature (°C) (Shade DBT)		
Month	Solar	Ordinary	Ambient	Solar	Ordinary	Ambient
December	17·0	5·2	0·4	9·5	1·2	−8·25
January	10·0	4·0	−3·0	4·0	−4·0	−14·0
February	13·7	6·2	−1·2	7·0	0·0	−12·4
March	15·0	10·0	4·7	9·0	3·5	−3·5
April	19·2	18·5	15·8	13·7	11·5	2·0
May	21·5	19·8	15·5	15·9	11·3	4·5

Solar room = glazed masonry wall, vented Trombe recorded for a full heating season at three hourly intervals. Typical monthly means recorded are given in table 3. Steady upward differentials of 8°C and above have been observed in the solar room under ambient conditions during the coldest months when the sun is at low elevation and the Trombe wall is most effective. Assuming room heaters burning wood to have an efficiency of 24%, the equivalent wood saving is 5·7 tons of firewood/heating season. Similarly, for kerosene oil/wood *bukhari*, the net saving is 992 litres of kerosene oil for one heating season per family. This is assuming that only a single room is heated in normal hours and 18·3°C is considered comfortable for local residents.

6.3 *Sky-therm studies for cooling in Bangalore – roof pond*

Prasad *et al* (1979) developed a simulation model and an experimental building to validate it for the Sky-therm system with a view to employing the technique for tempering the climate of storage rooms for sericulture, which have to be kept at a temperature of (25 ± 3)°C throughout the year. These experimental studies were done in Bangalore, as sericulture is a major cottage industry in the surrounding area.

The low cost building used for this purpose had walls made of plastered and stabilised mud blocks (machine-pressed) 30 cm thick and a ferrocement roof 3·75 cm thick. Because of large glazed areas on south and west walls (18% of floor area) and permanent ventilation resulting in one air change per hour at velocities of 5 km/h (even when fully closed), the building was not really suited for the cooling part of the Sky-therm system.

However, it could be the norm in improved low cost housing and hence may be considered as realistic.

Ten-centimetre thick water bags on the roof, which allowed for radiative as well as for evaporative cooling when open, decreased the indoor air temperatures by 3–4°C during the hottest month of April, when shaded by wooden boards during

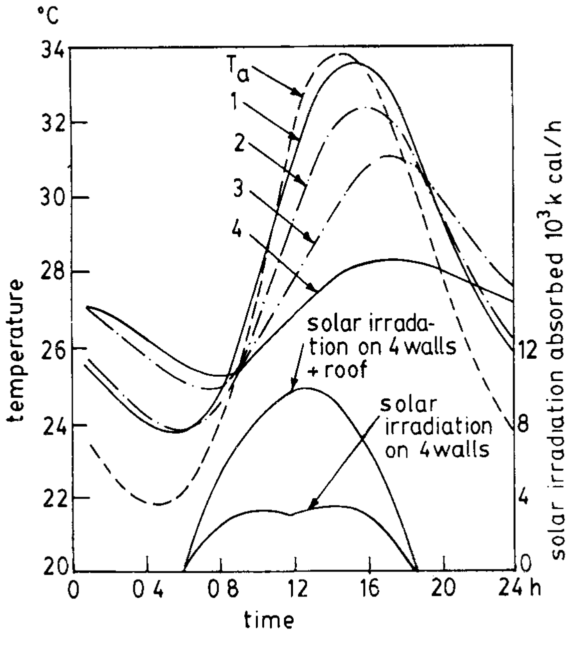

Figure 9. Roof pond system temperature profiles – Bangalore (1 – Concrete building, 10 cm thick walls, 10 cm thick roof; 2 – concrete roof, shaded; 3 – brick building, 30 cm thick mud-brick walls, 3·75 cm thick ferro-roof, shaded; 4 – water (10 cm depth) on top of the brick building, movable insulating cover over the roof opened after 7 p.m.)

the day, even though shading permitted some air leakages. Measured profiles of daily temperatures are shown in figure 9. Also shown in figure 9 are simulated results for a prefabricated concrete building using 10 cm thick elements for walls and roofs, with and without shading. The cooling achieved, as well as the reduced temperature swing, is striking.

6.4 *Building fabric evaporative cooling, Roorkee – roof fabric system*

This concept, due to S P Jain of CBRI, Roorkee (Jain & Rao 1974), and initially considered suitable for thin roofs, converted such roofs from net donors with 40 to 50% of sensible heat gains to effective heat sinks. The technique has been subsequently applied to residential and office buildings in hot, dry climates for reduction in temperatures of non-AC buildings and for load reduction in AC buildings to the extent of 30% (Jain 1989). Figure 10 shows the Modipuram Factory folded plate roof being covered with jute coir matting for the purpose (600 m^2 covered area).

A cheap water-retaining fabric has been used so that wetting is needed only thrice during 24 hours for 10 minutes to 30 minutes each time; the average consumption of water being 10 l/m^2 per day during summer. An additional advantage of complete elimination of temperature gradient and overhead stratified hot air is also realised as ceiling peak temperatures drop by 15°C and more. Measured temperatures for treated as well as untreated rooms are given in table 4 for various types of buildings (Jain 1989). This system is also being installed at Navodaya Vidyalaya, Sultanpur (Jain 1990, personal communication).

6.5 *Residential building (S M Jauhri, New Delhi, 1976) – terrace garden cooling*

Terrace gardens are often thought of as an efficient passive energy technique for cool living areas below. The coolth from the transpiration of plants is thought to descend down into the rooms. However, the coolth comes from the water in the

Figure 10. Roof fabric system at Modipuram – laying of coir matting.

Table 4. Roof fabric cooling.
Effect of the cooling process on low-cost/modern buildings on similar hot summer days. Average ambient maximum and minimum temperatures: 42·0 and 22·0°C, respectively.

Building	Specifications	Approximate maximum indoor air temperature °C at living level		Drop in indoor air temperature (°C)
		Untreated	Treated	
Conventional	Walls: 23·0 cm thick solid brick Roof: 11·4 cm RCC plus 10·2 cm lime concentrate	40·0	32·0	8·0
Low-cost/ modern	Small annex of soil engineering division of CBRI with low height (2·6 m) larger glazed windows facing west exposure	41·5	32·0	9·5
Low-cost/ modern	CBRI light-weight fully exposed hut with walls 15·0 cm thick, roofs 13·0 cm thick treated with tarfelt and low ceiling-height (2·7 m).	42·0	32·0	10·0
Low-cost/ modern	A modern office complex with rooms having fully glazed fronts, floor areas (2·4 × 2·1 m), low ceiling-height (2·6 m) and 10 cm RCC roof treated with tarfelt, at Chandigarh	42·0	32·0	10·0
Low-cost/ modern	CBRI extension centre at Bhopal having roof of 5·0 cm precast roofing units, walls mostly exposed	41·0	32·0	9·0
Low-cost/ modern	Prototype having galvanised-iron sheet-roof	42·5	32·0	10·5
Low-cost/ modern	Prototype having Trafford asbestos-cement sheet-roof	42·5	32·0	10·5

soaked gravel and mud layer, which on evaporation takes away heat from the room below and hence succeeds in cooling it. Hence the plants have little role to play in the cooling of the rooms except for increasing the specific surface area of evaporation. This system is a part of the architect's vocabulary and has recently been used by V K Gupta (personal communication).

As compared to roof fabric cooling, the roof deck becomes thicker and there is time-lag in cooling because of conductive heat transfer, rather than convective, as in ponds, or direct contact, as in case of roof fabric systems. The system works best during summers, is ineffective in monsoons and provides additional insulation in winter, if not irrigated.

6.6 *Office building – Muthukumar, New Delhi (1989–90) – earth air tunnel*

It is an office building and forms part of the Indian Institute of Technology–German project. A specially designed earth air tunnel for cooling the rooms (especially the computer room) by sucking in air via blowers and carrying it through a 15 cm stoneware pipe, 3·25 m below the ground, has been planned and constructed at the Delhi campus of the Indian Institute of Technology.

No conventional airconditioning for the summer months or fuel-based heating of the building is planned for winters. The whole building is an energy-conscious design right from the planning stage and incorporates many low-energy features such as mud construction, skylights on Nubian vaults, domes for daylighting and hot air venting, and proper orientation (Duggal 1986, unpublished). Figure 11 shows. the plan and a section of the building.

The building is being monitored for one year since May 1990 to check on the results of computer simulations already made. Another earth air tunnel system has been incorporated recently into the construction of the Indira Gandhi National Centre of Art exhibition building, designed by Development Alternatives (S Prakash 1990, personal communication).

6.7 *Farmhouse (N Manchanda, New Delhi) – induced ventilation*

This farmhouse design uses a wind tower over the foyer to effect induced ventilation (figure 12) and is yet to be built. It also has a vented 2 m high dome over the sunspace

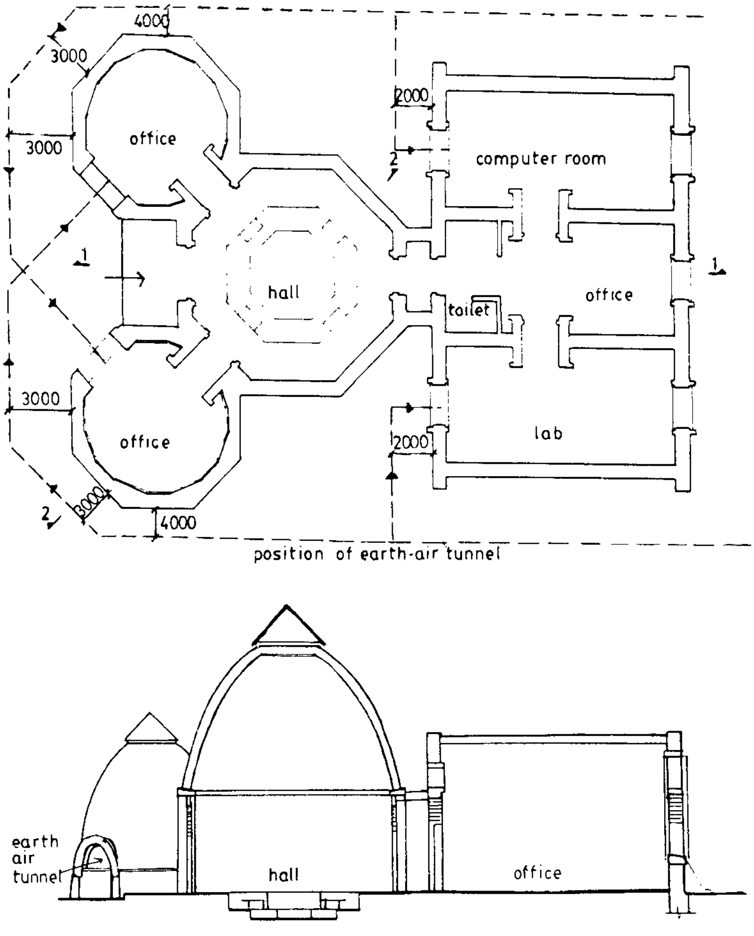

Figure 11. Earth tunnel air-cooled office – plan and section.

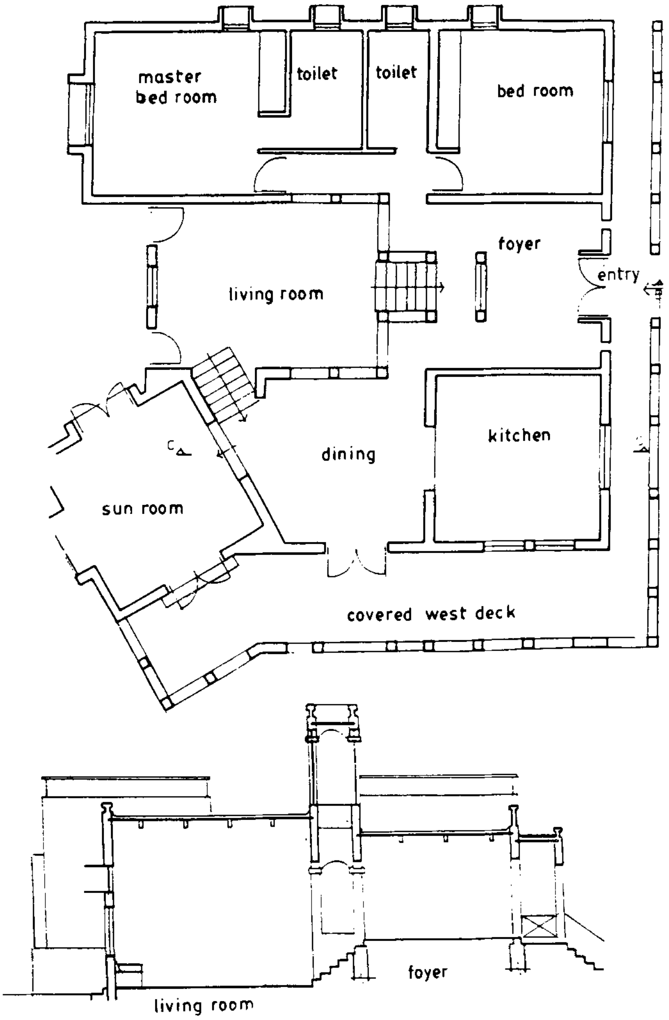

Figure 12. Tower over foyer of a farm house – induced ventilation.

to induce slight air movements during sun-up hours giving a pleasant and comfortable feeling.

Further, the roof dome has been painted white to reflect the sun's rays and cavity walls have been used to achieve reduction in heat transfer. Deep overhangs have been designed on west- and south-facing surfaces to prevent overheating during summer without excluding the sun during winter.

6.8 *Navodaya Project, Sultanpur* (*CBRI, 1989*) *– passive convective loop*

This Navodaya School building, under construction at Sultanpur, UP, is proposed to be retrofitted with convective loop vertical heaters for its class rooms (C L Gupta, S Roy, V Geeta 1988, unpublished). These will heat the indoor air in winters during sun-up hours, which coincides with school working hours. A thermosyphon convective loop, whose system has been built into the vertical louver space, figure 13, heats the air and circulates it. The working of the heater is explained in figure 14. Room

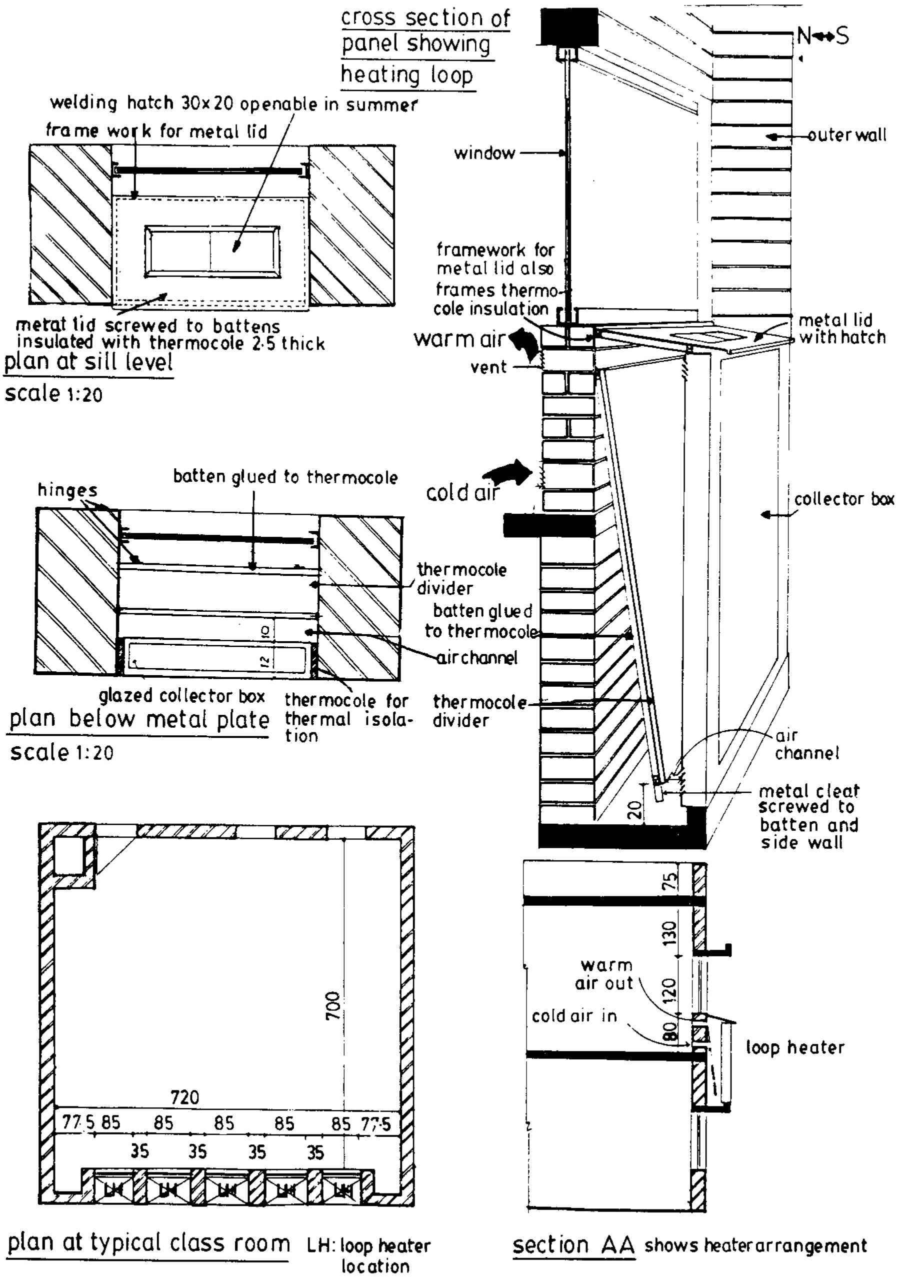

Figure 13. Navodaya Vidyalaya, Sultanpur – convective loop.

temperature is expected to rise by 7 to 8°C above the ambient for working hours during winter, making it pleasant and comfortable.

7. Benefits and costs

Before assessing the conventional economics of solar passive buildings, it is pertinent to note some features of significance, particularly for developing countries, which are

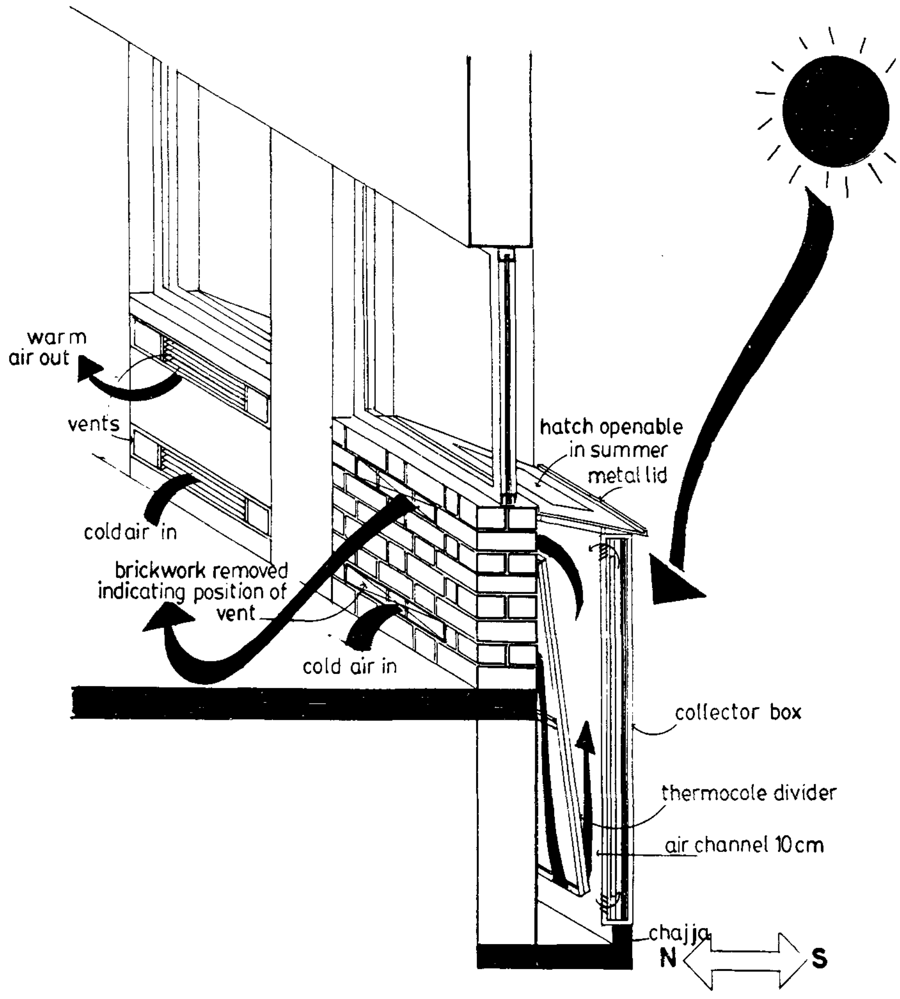

Figure 14. Working principle of a convective loop air heater.

supply-constrained with respect to financial and conventional fuel inputs. These are as follows.

7.1 *Significant non-fiscal benefits*

7.1a *Capability for progressive retrofit*: Passive measures can be progressively retrofitted to existing buildings as skills, need, time and resources permit. The right balance of manual effort and automation can be designed for operating the system. Also the right mix of fresh air and recirculation, daylighting and artificial lighting, temperature swings on daily/seasonal basis can be prescribed and designed for.

7.1b *Social suitability for non-conditioned building users*: Passive buildings do not need auxiliary back-up if well designed because of large thermal time constant of buildings having good insulation and large mass. They are natural extensions of good bioclimatic design and energy conserving buildings, employing good insulation and controlled infiltration.

7.1c *Responsiveness to variable climates*: Passive buildings for heating tend to collect even very low levels of solar radiation; in those for cooling, small depressions of night sky temperatures below the ambient also boost the radiant cooling of the roof deck.

7.1d *Low energy constructions*: Most of the materials and skills employed are from the construction industry and hardly any metal/welding etc. is used as for solar active systems. Parasitic operating energy costs are almost nil in the absence of moving parts, thereby also cutting maintenance costs and reducing down-time. Mud as a building material, wherever normally employed, is quite suitable for passive-retrofit or as basic material for new constructions.

7.1e *Thermal comfort and aesthetics*: Apart from attenuating indoor temperature swings and increasing ΔT with respect to outdoors, radiant panel heating and cooling are far more comfortable as compared to convective systems. Naturally convecting currents hardly produce drafts and radiant panels around body temperature do not adversely affect the environmental temperatures. Only in the case of direct systems, drapes and movable insulation have to be considered to avoid large hot/cold surfaces and to reduce glare. Passive solar buildings can have dramatic facades but are not more or less appealing than other architect-designed buildings.

7.1f *Energy autonomy and reliability*: A well-designed passive building is rarely 'down' as all movements have nature induced driving potentials. These are energy autonomous and are usually immune to power-cuts, which are commonplace these days. However, as in the case of ordinary good buildings, they need sensitive and conscious handling to be at their best.

7.2 *Fiscal costs*

Incremental costs of retrofit installations or *ab initio* designed passive buildings, vary with baseline building costs and logistics of the location, apart from the type of system employed. Even though not too many well-documented passive buildings have been made in India so far, the following costs as percentage fractions of baseline costs can be taken to be fairly reliable economic indicators.

7.2a *Heating systems*: (i) *Direct gain system* – Unit area costs of simple single-glazed windows are usually twice the 22·5 cm brick wall costs, thrice the 45 cm thick mud wall costs and 1·6 times the 15 cm thick concrete wall costs. Sodha *et al* (1989) have tried to optimize the area of direct systems and thermal storage walls for cold climates for maximum savings in annual energy costs. Window areas for direct systems work out to be 24% for mud walls and 37% for concrete walls at above costs, both values being percentages of south wall areas.

(ii) *Isolated gain (attached sunspaces)* – Single-glazed greenhouses have been attached to mud houses in the Ladakh region. They cost (at 1981 prices) Rs 260/m^2 of floor area, about 43% of the cost of mud buildings as traditionally made. The glass costs alone were 40% of the greenhouse costs because of the difficult logistics of the cold hilly areas. In colder regions on the plains, assuming cladding costs to be the same (with lesser material but higher labour costs), these will amount to about

20% of building costs for the usual brick building with an RCC roof and mosaic flooring (A class finish as per CPWD norms) with south-facing glass areas no more than 66% of the floor area.

(iii) *Indirect gain* (*glazed masonry walls*) – For double-glazed systems, retrofit costs are nearly twice the cost of single-glazed greenhouse cladding. As such, the incremental costs are really the same as the building costs for mud buildings and nearly 40% of that for brick/concrete buildings, with glazed areas being 66% of floor areas for less. Actual figures for Leh in the Ladakh region (3500 m above sea level and at 1979 prices) for a room of 22·5 m^2 floor area, newly designed and constructed: solar-system costs – Rs 9,000 (Norberg 1980); with wall/floor areas being 63% and glass being 30% of the system cost.

7.2b *Heating and cooling systems*: (i) *Roof pond with variable shading* – This system has been tried on an experimental building with a ferrocement roof in Bangalore (Prasad *et al* 1979) and on a poultry shed with a specially designed 7·5 cm thick RCC grid roof in New Delhi (Gupta & Jauhri 1978). The incremental costs for additional water proofing, variable shading and water delivery and disposal system amounted to 25% of improved poultry building cost with an RCC grid roof. This type of poultry building costs 20% more than traditional poultry buildings with AC sheet roofing (which cost Rs 180/- per m^2 in New Delhi at 1977 prices) but has twice the life. Current cost fractions could be reasonably considered to be of the same order.

7.2c *Cooling systems*: (i) *Roof spray with coir matting* – This system (Jain & Rao 1974; Jain 1989) has been tried on many types of buildings, e.g. office, residential, school, hotel and factory buildings. The costs vary considerably depending on whether one uses discarded empty cement bags (of jute) with garden hoses for manual spray or a fully automated spray using specially designed open-weave coir-matting. Design capital costs can be considered at 5% for office buildings and 10% for factory buildings per unit floor area. For the best systems, resultant savings of 60% in capital costs of AC plants and of 30% in running costs of AC plants have been reported. Running costs of this system are costs of water at 10 litre/day/m^2 of roof area and 2 to 3 kWh of electric consumption per 100 m^2 of roof/month, which is minimal and could even be supplied by solar photovoltaic panels.

7.3 *Unit energy costs*

Unit energy costs vary with baseline building costs, climate of location, season/year round use and purpose and type of system employed. Calculations have been done for the hot dry climate in northern India, assuming that the system's life, interest rates and inflation rates are such that 10% capital recovery factor can be ensured. On this basis, unit energy costs (1988) for seasonal use vary between Rs $\langle 0{\cdot}27, 0{\cdot}37\rangle$ per kWh of thermal energy. Capital costs for installation vary between Rs $\langle 6667, 23000\rangle$ per kW installed (C L Gupta, S Roy & V Geeta 1988, unpublished). These are estimated costs and are not based on actual monitoring.

8. Concluding remarks

(1) Solar passive buildings have now become a part of design vocabulary in the building field all the world over. It is bound to spill over to developing countries

initially for 'paying' uses such as recreation homes and tourist resorts in cold hilly regions, and later for energy saving in offices and for reducing thermal stress in hospitals, factories and houses.

(2) Current trends internationally are towards hybrid systems, e.g. integration of energy conservation and solar passive features (Balcomb 1987).

(3) Current trends in India are towards integrating solar passive features with on-site power and waste recycling systems for design of campus communities, as evidenced by a large number of training courses offered and design competitions being organised e.g. GEDA (1990).

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