References

1. Solow, Robert M., Umweltverschmutzung und Umweltschutz aus der Sicht des Ökonomen, in, Möller, Hans *et al.*, Umweltökonomik. Beiträge zur Theorie and Politik. Königstein 1982, p. 30–42.
2. Wicke, L., Die ökologischen Milliarden. Das kostet die zerstörte Umwelt – so können wir sie retten, München 1986.
3. Barbir, R., T. N. Veziroglu and H. J. Plass, Environmental Damage Due to Fossil Fuels Use. In: *International Journal on Hydrogen Energy*, **15**, 10, pp. 739–749, 1990.
4. Pigou, A. C., Wealth and Welfare, London 1912.
5. Kapp, K. William, The Social Costs of Private Enterprise, Cambridge, 1950.
6. Kapp, William S., Soziale Kosten der Marktwirtschaft. Frankfurt 1979.
7. Schneider, H. K., Implikationen der Theorie erschöpfbarer natürlicher Ressourcen für wirtschaftspolitisches Handeln, in: *Erschöpfbare Ressourcen*, H. Siebert (ed.), Berlin 1980, p. 815–844.
8. Hohmeyer, Olav, *Social Costs of Energy*. Berlin, Heidelberg, New York 1988.
9. Ottinger, Richard L. *et al.*, Environmental Externality Costs of Electricity. Ocean Publications, New York, London, Rome 1990.
10. Contemporary Policy Issues, Vol. VIII, No. 3, 'Social and Private Costs of Alternative Energy Technologies' Huntington Beach, California 1990.
11. Hohmeyer, O. and R. L. Ottinger (eds.), '*External Environmental Costs of Electric Power Production*' Springer-Verlag, Berlin, Heidelberg, New York, 1991.
12. Hohmeyer, Olav, *Soziale Kosten des Energieverbrauchs*. 2. edition, Berlin, Heidelberg, New York 1989.
13 Hohmeyer, Olav, 'Social Costs of Electricity Generation: Wind and Photovoltaic Versus Fossil and Nuclear', Contemporary Policy Issues, Vol. VIII, No. 3, July 1990, pp. 255–282.
14. Hohmeyer, Olav, 'Least-Cost Planning und soziale Kosten', Peter Hennicke, ed., Least Cost Planning – Ein neues Konzept zur Regulierung, Planung und Optimierung der Energienutzung, Springer-Verlag Berlin, Heidelberg, New York, 1991a.
15. Hohmeyer, Olav, 'Adaequate Berücksichtigung der Erschöpfbarkeit nicht erneuerbarer Ressourcen', Paper presented at the Seminar Identifizierung und Internalisierung externer Effekte der Energieversorgung, Freiburg, 19.4.91b.
16. Koomey, Jonathan, Comparative Analysis of Monetary Estimates of External Costs Associated with Combustion of Fossil Fuels. In: New England Conference of Public Utilities Commissioners: Environmental Externalities Workshop – Papers Presented. Portsmouth New Hampshire, USA, No place 1990.
17. GRS (Gesellschaft für Reaktorsicherheit mbH), Deutsche Risikostudie Kernkraftwerke Phase B. Eine zusammenfassende Darstellung. No place, 2. Ed. October 1989 (1. Ed. June 1989).
18. Buchanan, Shepard, Methodology for Determining "External Costs" of Environmental and Health Risks. Paper presented at a Hearing of the State of Massachusetts, October 12th, 1988 in Billerica, USA.
19. Ottinger, Richard L., Incorporation of Environmental Externalities in the United States of America. In: Hohmeyer and Ottinger: External Environmental Costs of Electric Power Production, Springer-Verlag, Berlin, Heidelberg, New York 1991, p. 353–374.
20 Voß, A., R. Friedrich, E. Kallenbach, A. Thöne, H.-H. Rogner and H.-D. Karl, Externe Kosten der Stromerzeugung. Studie im Auftrag der VDEW. Frankfurt 1989.

Int. J. Solar Energy, 1992, Vol. 11, pp. 251–271
Reprints available directly from the publisher
Photocopying permitted by license only

PASSIVE AND HYBRID COOLING OF BUILDINGS – STATE OF THE ART

M. ANTINUCCI,[1] D. ASIAIN,[3] B. FLEURY,[2] J. LOPEZ,[3]
E. MALDONADO,[4] M. SANTAMOURIS,[5] A. TOMBAZIS[6]
and S. YANNAS[7]

[1] *Conphoebus Scrl, Zona Industriale Passo Martino, Fermo Posta, 95030 Piano d Arci, Catania, Italy.*
[2] *LASH/ENTPE, Rue M. Aduin 69120, Vaulx en Velin, France. Now at AEROVIM, Azay Le Brule, 79400, St. Maixent L Ecole, France.*
[3] *Seminario de Arqitectura Bioclimatica, Escuela Superior de Arqitectura, Avda Reina Mercedes S/N 41012 Sevilla Spain.*
[4] *Universidade do Porto, Rua D. Manuel II, 4003 Porto Codex Portugal.*
[5] *University of Athens, Physics Department, Ippokratous 33, Athens, Greece. Author to whom correspondence should be addressed.*
[6] *Meletitiki Ltd, 75 Vassilissis Sofias str, 11521 Athens Greece.*
[7] *Architectural Association. School of Architecture. Energy Studies Programme, 34–36 Bedford Str. London, WCIB 3ES UK.*

(Received 25 March 1991)

This paper deals with the state of the art on Passive and Hybrid Cooling of buildings. The existing techniques and components to prevent thermal gains and to dissipate excess energy to environmental heat sinks are reviewed. Topics dealing with the control of internal heat gains and with the occupant activities are discussed. The state of the art on design tools is presented. Thirteen European buildings using passive and hybrid cooling techniques and components are analyzed. Finally, future research needs are discussed. This work summarizes the findings of a Horizontal study on Passive Cooling carried out by the authors (1), as part of the Building 2000 research program of the European Communities.

KEY WORDS: Passive Cooling, Buildings, Heat sinks

1 INTRODUCTION

Proper design of buildings requires a balance of heating, cooling and daylighting performance. Achievement of thermal comfort during summer and reduction of cooling loads by natural means, is considered now a first priority for electric utilities and consumers. The resulting peak electricity demand profiles and the very high cost of conventional cooling systems make the strategic management of air conditioning growth an important exercise for industrialized countries planners.

The development, in the 30's, of inexpensive, reliable Carnot cycle refrigeration systems, using electrically driven compressors, has made cooling widely feasible. During the past decades, air conditioning became widespread in residential and commercial construction. Annual purchases of air conditioning equipment had exceeded the $20 billion mark by the end of the 80's (2), while, the world trade in air conditioning and industrial refrigeration equipment has more than tripled in real terms during the decade 1976–1985 (3).

The increase of family income in Europe has made the use of air conditioning systems highly popular. Annual purchases of air conditioners in Greece have increased approximately 900 per cent during the last three years, while sales of air conditioners in Italy and Spain go side by side (4).

The impact of air conditioners usage on electricity demand is a serious problem for many developed countries. Peak electric loads oblige utilities to build additional power plants in order to satisfy the demand, thus increasing the average cost of electricity. This situation has become a serious problem in the United States, where the total electric peak load induced by air conditioning is estimated at 175 MW or 38 percent of non coincident peak demand, (5).

Important peak load problems during summer have been also experienced in Greece during the last few years (6). Environmental problems associated with the use of ozone depleting CFC refrigerants used on conventional air conditioners are an additional impulse for the definition of an alternative cooling policy.

Finally, recent comparative studies on indoor air quality in air conditioned and naturally ventilated office buildings have shown that illness indices are higher in air conditioned buildings (7–8).

Alternative cooling strategies based on improved thermal protection of the building envelope, and on the dissipation of building's thermal load to a lower temperature heat sink, appear to be very effective. These strategies and techniques known as passive and hybrid cooling have already reached a certain level of architectural and industrial acceptance. A survey of the European industry has shown that there are more than 200 industrial units producing more than 500 different products related to Passive and Hybrid cooling of buildings (9). It is reported that imports of evaporative coolers in Greece reach values close to 23 million dollars per year (9).

Where passive techniques are being considered as alternatives to air conditioning the following are some of the primary benefits:

—Environmental benefits: There are important indirect environmental benefits associated with the reduction of the CFCs, and the reduction of pollution caused by the production electricity.

—Indoor environmental quality and occupant health.

—Cost savings: These will include savings in capital, maintenance and running costs.

—Energy savings: The resulting savings in primary energy can be considerable.

—Reduced strain on national grids by reducing the peak electric demand.

—Simplicity, ease of operation: These are common characteristics but may vary between different processes and techniques.

The possible constraints and limitations to the application of passive and hybrid cooling techniques are related with:

—Climate, microclimate or site topography problems: Insufficient wind speeds, constraints in orientation, cloud cover, and high humidities are among the constraints that may be encountered at different sites.

—Conflict with other design requirements and with design measures for the heating season. Such conflicts are unlikely to be serious if designers establish their priorities from the outset.

—Economic and institutional constraints. While thermal insulation is now a mandatory requirement, the far more important issue of offering acceptable indoor conditions for comfort and/or health is not. This often acts as disincentive to developers geared toward minimising capital cost and maximizing profit.

—Lack of information, tools or precedents. This is a major constraint and a disincentive both for designers and developers.

The aim of this paper is to present the state of the art on Passive and Hybrid Cooling, to report on the current knowledge and on the recent achievements, to define the potential and the limitations of passive and hybrid cooling techniques, to investigate the existing scientific gaps and to propose priorities for future research actions.

This paper summarises findings of a Horizontal Study on Passive Cooling carried out by the authors, inside the Building 2000 research program of the European Communities (1).

2 DEFINITIONS

As with passive solar heating and passive solar design, the study and application of passive cooling is a multilayered and multidisciplinary process. It is especially important to treat the subject in conjunction with other aspects of architectural design and in the context of an overall environmental design strategy. From such a view point, passive cooling processes should not be considered as isolated phenomena but in close relationship to building types, occupancy patterns and the sources of heat gain to buildings in the various climatic conditions. A useful framework for considering passive and hybrid cooling in the context of environmental design is under the following three steps: Prevention of (or protection from) heat gains; Modulation of heat gains and heat dissipation.

Protection from heat gains may involve the following design measures:

—landscaping and the use of outdoor and semi-outdoor spaces

—building form, layout and external finishings

—solar control and shading of building surface

—thermal insulation

—control of internal gains

Such measures tend to be generally applicable under all types of climate and site conditions and are relevant to all building types.

Modulation of heat gain has to do with the capacity for heat storage in the building structure. This delay strategy can provide attenuation of peaks in cooling load and modulation of internal temperature with heat discharge at a later time. The larger the swings in outdoor temperature are, the more important the effect of such storage capacity is. The cycle of heat storage and discharge must be combined with means of heat dissipation, commonly night time ventilation and/or radiative cooling, so that the discharge phase does not add to overheating.

Heat dissipation techniques deal with the potential for disposal of excess heat by natural means. Dissipation of the excess heat depends on two main conditions:

(a) The availability of an appropriate environmental heat sink for the heat to be rejected.
(b) The appropriate thermal coupling and sufficient temperature differences for the transfers of heat from indoor spaces to sink. The main processes of heat dissipation techniques are identified in the table below.

Process	Heat Sink	Main Heat Transfer Mode
Radiative Cooling	Sky	Radiation
Evaporative Cooling	Air	Evaporation
Convective Cooling	Air	Convection
Ground Cooling	Earth	Conduction

Heat dissipation processes are generally climate dependent. Heat transfer may be assisted by mechanical devices as a means of overcoming low temperature differences or other limitations.

3 PREVENTION AND MODULATION OF THERMAL GAINS

3.1. *The Role of Microclimate*

Modifications of the microclimate around buildings can help to improve indoor comfort conditions and to reduce cooling loads, while also providing protected spaces for outdoor uses. Siting and site layout as well as landscaping represent the two important groups of strategies to improve the microclimate around buildings.

Appropriate siting of a building can provide natural solar protection and help to take advantage of local winds and breezes. Nearby mountains, valleys, lakes and sea may enhance these effects. Important information on staggered layouts enhancing the potential for cooling load is given in (10).

Landscaping can play an important role in microclimate modifications in both overheated and underheated conditions. Useful information to modify microclimate using appropriate landscaping is given in (11–12).

Vegetation provides natural protection from the sun. Moreover vegetation is a natural form of an evaporative cooler. Trees are commonly used for shading and their characteristics are listed in (13–14). A detailed sample of landscape materials and the corresponding characteristics are given in (15).

Current knowledge on the role of vegetation results mainly from observations. Temperature reductions of about 2–3°C due to evapotranspiration are reported in (16–19). Important information can also be gained from theoretical analyses. It is reported that evapotranspiration from one tree can save 1–2.4 MJ of electricity in air conditioning per year (20), while an average full sized tree evaporates 1460 kg of water per sunny day which is the equivalent of 870 MJ cooling capacity (21). It is also stated that the latent heat transfer from wet grass can result in temperature 6–8 C cooler than exposed soil, and that one acre of grass can transfer more than 50 GJ/day (21).

Other landscape techniques include the use of pools or ponds, fountains or sprays and cascades for evaporation. According to (22), under mean conditions of wind, dry and wet bulb temperature, the energy released by a square meter of open water surface is close to 200 Joules.

Possible limitations to the application of the above strategies and techniques may be due to planning constraints, lack of water resources, high maintenance costs, lack of land, lengthy required time period for plant growth and low priority of landscaping as the last of construction process. Although the knowledge acquired on this field is satisfactory, a better understanding of the physical processes involved is necessary. For this purpose research should be carried out involving field experiments and development of evaluation methods, based on analytical techniques, while heat island effects should be examined in more details.

3.2 *Building Form*

Building form and the disposition of internal or intermediate spaces can play a role as regulators of exposure to incident solar radiation and natural light; exposure to wind, and channelling of air movement within and around a building.

Where choice of form exists, the inherent compactness of different building forms may be exploited to advantage, perhaps especially so when reinforcing or facilitating specific heat dissipation processes as well. For example, the open courtyard form, maximisation of roof surfaces for radiative cooling, construction on pilotis, and use of wing walls are some of the ways in which building form may be manipulated to support heat dissipation processes.

Building shape may be used as a means for reducing or increasing the ratio of exposed surface to volume. Low surface to volume ratios suggest a compact form with a comparatively low exposed surface offering advantages for controlling both heat losses and heat gains. However, the effects of form on wind channelling and air flow patterns are important and have not yet been studied adequately. Similarly, the possibility for enhancing daylight by manipulation of building form deserves more attention.

Planning regulations, site conditions and the position of adjacent buildings: architectural styles, client preferences and cost constraints tend to limit the degree of freedom available for manipulating building form and shape. Multi-storey blocks arranged in rows of varying length are very common in Southern Europe. Such configurations, which are characterized by low surface to volume ratios and comparatively low exposure do not allow designers to control aspects such as orientation, siting and building form.

Thermal zoning is commonly recommended as a thermal buffering strategy and design guidelines are often given in the literature regarding zoning and the disposition of rooms in plan and section. Also, the disposition of rooms, and a building's general layout, will have an important effect on indoor air movement and on the potential for cross ventilation (23). Unglazed intermediate spaces such as verandas, arcades, or courtyards may act as tempered microclimates in their own right, as well as have a role in terms of wind channelling and solar protection for adjacent openings and surfaces (24).

Intermediate spaces such as conservatories which may be incorporated into a design as part of passive heating strategy can add to the cooling loads of the parent building.

3.3. *The Role of Solar Control and Shading*

Solar control is one of the most important strategies for heat gain prevention. Its role focuses on:

(a) The prevention of solar gains on buildings or landscape surfaces, occupant clothing or skin and
(b) The regulation of daylight and the protection of occupants and room contents from glare and ultraviolet radiation.

Effective design of solar control in a building should aim to balance cooling, heating and daylighting in the building. Reduction of the cooling load during summer, maximum utilization of the solar radiation during winter, and achievement of optimal daylight levels are among the basic objectives of the solar control techniques.

A complete review of solar control techniques as well as design considerations and solar control objectives are given in (25).

Design procedures have been proposed by various authors. The most important ones are reported in (26–29). However, the work of Aladar and Victor Olgyay's (26), published some twenty five years ago, is still the most comprehensive and most widely quoted work on the subject. Modelling of shading devices and their impact on ventilation, lighting and occupant comfort remains the major weakness of most building performance evaluation models. This weakness in knowledge is reflected in practice, leading to a number of non technically satisfactory applications.

Considerable developments have been achieved in glazing technology, both through improvements in thermal properties and through applications of optically controllable materials. Optical switching films, multilayer low-emissivity coatings and transparent insulation materials are some of the more important expected products.

3.4. *The Role of Thermal Mass*

Internal walls, partitions, and floors, as well as furniture, can provide thermal storage capacity. This is often referred as thermal mass. Thermal mass can play the role of a regulator, smoothing temperature swings, delaying peak temperature, decreasing mean radiant temperature and providing better comfort conditions.

Optimisation of the thermal mass levels inside a building depends on various parameters. Climatic conditions, occupancy patterns, building orientation, and the use of auxiliary heating and cooling system are among the more important.

Classification of buildings according to thermal mass and the related thermal performance is given in (30–31). Methods to optimize the thermal mass of a building have been proposed in (32–39). An evaluating discussion on some of these methods is given in (40–41).

Repertories of many wall compositions has been developed and proposed in (42), and the attenuation and time delay of a temperature wave is calculated.

Thermophysical characteristics of local materials used for building constructions are also reported in (43). Experiments using variable levels of thermal mass in similar buildings are reported in (44). It is found that increase of the internal mass from 21 Kg per square meter of floor to 201 kg, in close and in ventilated buildings, reduces the peak indoor temperature by about 1.0 and 2 C respectively.

Theoretical analysis based on intensive monitoring of office buildings (44), have shown that important reductions in peak heating and cooling loads was observed for high thermal mass designs. Energy savings varied from 18 to 20 per cent compared to a base case.

However, optimization of thermal mass in buildings requires further research.

4 USE OF ENVIRONMENTAL HEAT SINKS

4.1. *Ventilation*

Ventilation provides cooling by using air to carry heat away from the building and/or from the human body. Air movement may be created by natural forces (wind and stack effect) or by use of mechanical power (fan). Diverse strategies can be adopted to obtain benefits from natural ventilation.

The distribution and shape of the openings is a key element for efficient natural ventilation. Quantitative and qualitative aspects of cross and single sided ventilation techniques as well as roof opening techniques are discussed in (45–46). Selection of the appropriate window type and shape is necessary in order to optimize cross ventilation. However, a compromise has to be realised between daylighting, weatherproofing, structural strength, solar gain, operation, maintenance, cost and air movement control. Research, (47–48), has shown that horizontally shaped windows create greater interior air velocities than vertical windows. A typology of various window styles and their impact to ventilation is given in (49).

Wind tower techniques have been used in traditional architecture to capture wind and generate air movement within the building. Various architectural integrations of the system are presented in (49). Design information and performance calculation procedures are given in (50–51).

Solar chimneys are constructions used to promote air movement throughout the building using the solar gains. Are positioned at the sunward side of the building to make the best use of the solar heat gains. Performance analysis of such systems are performed in (52–54).

The use of wingwalls, proposed in (55), can considerably enhance cross ventilation (56). It is found that for oblique winds, the average room airspeed in a room with wingwalls was about the 40 percent of the outside wind compared with about 15 percent for the room without the wingwall. Vegetation affects the air flow pattern in the same way as outside buildings or wingwalls (57). Moreover, it also offers air filtering, noise reduction and shading.

Nighttime ventilation offers a high potential for building cooling because of the lower outside temperature. Performance data reported in (58–60), show that this is a powerful technique. A method to estimate the night ventilation potential is proposed in (61). Nighttime ventilation techniques, when natural, could face problems of building security and occupant privacy.

A box fan, an oscillating fan or a ceiling fan can supplement the effectiveness of natural ventilation by increasing the interior air velocities and convection exchange (62–63). Recent research, (64–65), has demonstrated the capability of fans to extend the summer comfort within the building outside the typical comfort zones. Oscillating fans present high potential at the local level to reduce the cooling load of the building. More research is needed to present guidelines on the use and potential of fans in hot climates.

4.2. *Evaporative Cooling*

Evaporation occurs whenever the vapour pressure of water, in the form of droplets or a wetted surface, is higher than the partial pressure of the water vapour in the adjacent atmosphere. When the decrease in the dry bulb temperature of the air is accompanied by an increase in its moisture content, the process is known as "direct evaporative cooling" and is characterized by a displacement along a constant wet bulb line. When the evaporation taking place inside a tube or on a surface results in a decrease of surface temperature, the temperature of the adjacent air is decreased without increase of its moisture content. In this case the process is known as indirect evaporative cooling and is characterized by a displacement along a constant moisture content line.

Evaporative cooling techniques are classified also as passive or hybrid. Therefore, four major categories of systems and techniques can be identified:

—Passive direct systems and techniques

—Passive indirect systems and techniques

—Hybrid direct systems and

—Hybrid indirect systems.

Passive direct systems and techniques include the use of vegetation for evapotranspiration; the use of fountains; sprays and pools; volume and tower cooling techniques.

Volume cooling techniques are known from traditional architecture. A contemporary version of this technique was presented in (66). Here a wet cellulose pad is installed at the top of a downdraft tower, below the roof, where the air is humidified. Measurements reported in (67), show a very good performance of the system.

Passive indirect evaporative techniques include the roof spray, open water pond and moving water film techniques. In the roof spray technique, the exterior surface of the roof is kept wet using sprinklers. Cooling of the building is achieved by conversion of the sensible heat of the roof surface into latent heat of vaporization. Experience acquired through many commercial applications in the United States, (68) shows that reduction in cooling load close to 25 per cent is possible. However, important operational problems, reported in (68), are associated with this system which has been abolished from any further developments.

In an open roof water pond, evaporation of the water to the dry atmosphere occurs during night time. Thus, indoor and radiant temperatures can be lowered without elevating indoor humidity levels. Knowledge on this technique is developed through experiments described in (69–71), and simulations given in (72). A decrease of the ceiling temperature between 2 to 13 C has been reported. However, important limitations associated with this technique have not permitted its wide application.

The moving water film technique is based on the flow of a water film over the roof surface. The evaporation process is enhanced by an increase in the relative speed between air and water surface. The cooled water is stored in the basement and is then circulated within the room to cool it. Knowledge on this technique has been developed through limited experiments described in (73). Results show that the application of this system is more suitable for humid climates.

Hybrid direct evaporative systems involve the use of fibrous pads where the air is drawn and cooled by evaporation of flowing water. Thus, dry bulb temperature is reduced while its moisture content is increased. In order to increase the efficiency of the system various type of technologies have been proposed. Detailed description of the systems is given in (74).

Hybrid direct evaporative coolers are in use for more than 50 years. Important industrial experience is achieved mainly in Australia and in United States, while last figures show an important market in Europe (9). The efficiency of the system is seriously affected by local climatic conditions. The coolers are mainly suitable for places characterized by low wet bulb temperature. Performance data for fourteen Mediterranean locations are given in (4).

The main problem associated with direct evaporative coolers is the increase of the moisture content of the indoor air. Humidity control systems should be always combined with the system.

Hybrid indirect evaporative cooling systems are based on the use of a heat exchanger where the indoor or outdoor ventilated air passes through the primary circuit where evaporation occurs while the outdoor air passes through the secondary circuit. Thus the temperature of the air is decreased without any moisture increase.

Important industrial development of the system has been achieved during the past few years. Three main type of indirect coolers are available: Plate, tubular and rotary type coolers. Detailed description of the systems is given in (74).

Performance data on plate coolers developed at CSIRO, Australia (75), show that energy savings of up to 60 per cent can be achieved compared to compression refrigeration systems. However, the efficiency of the system is strongly influenced by the wet bulb temperature of the ambient air. Performance evaluations of the system for various European locations are given in (9).

Where the ambient air is too high, a two stage evaporative system can be used. This consists of an indirect cooler coupled with a direct one. There are many applications of these systems, especially in California. Energy savings for such a system have been reported at close to 50 per cent compared to an equivalent A/C system (74). Performance data for 14 European locations are given in (4).

4.3. *Ground Cooling*

Ground or earth cooling is based on the temperature difference between soil and the atmospheric environment. During the summer, the soil temperature at certain depth is considerably lower than the ambient temperature and therefore offers an important source for the dissipation of the building excess heat. The relative ranges of the soil temperature as function of depth for various types of soil is given in (76).

There are two main strategies for the dissipation of heat to the ground: direct ground contact cooling and indirect or buried pipes technique. Direct ground contact cooling involves partial or total placing of the buildings envelope in direct contact with the soil. This technique based on the transfer of heat from the building to the ground through the walls, floor and possibly the ceiling has been used at different times in history and in different parts of the globe. Important underground dwellings, villages and communities have been also developed in the Mediterranean region, (77–80). A classification of the earth sheltered buildings is given in (81).

Important advantages and disadvantages of earth contact buildings are reported in the literature (81). Estimates of the number of earth sheltered houses in USA in 1982 range from 4000 to 8000, (81).

Knowledge on the performance of earth sheltered buildings comes mainly from measurements of traditional buildings, (82), from monitoring of new constructions, (83–84), as well as from theoretical analysis, (81). Energy gains of about 50 to 90 percent are reported for various monitored earth sheltered buildings (83–84).

Underground cooling tunnels is a concept that can be traced back several centuries. Applications of these techniques at different times and in different parts of the world are described in (85–87). The concept involves the use of a metallic, PVC, or concrete pipe buried at 1 to 3 m depth. Ambient or indoor air is delivered inside the tubes where it is precooled and then delivered to the building.

Knowledge on the topic is coming mainly from single pipe experiments (88–95), multi-pipe installations, (96), as well as from theoretical analysis. Techniques to estimate the efficiency of such systems have been developed and proposed in (88, 90, 91, 92). An evaluating revue of the proposed algorithms is given in (97).

Results reported on the performance of buried pipes, show that for a 30 m long PVC pipe buried under shaded soil at 1.5 m depth, the maximum temperature drop was 18°C. However the temperature reduction is time dependent. Results for 120 hours of continuous operation are given in (96).

Special problems related to this technique is the limited potential for dehumidification, reducing thus the possibility for latent heat cooling. Condensation inside the tubes can occur only with low air flow and high ambient dew point temperatures. Also in the event of damaged tubes, water, could enter into the tubes. Moisture accumulation can lead to biological growth and cause odour problems. However, no such problems have been reported.

4.4. *Radiative Cooling*

Radiative cooling is based on the effect of heat loss by a body due to its long wavelength radiation to the night sky. The net energy loss from a body is the balance between the net radiative loss and the convective heat exchange between the radiator and the ambient air. As net radiative loss we define the difference between the emitted energy flux and the absorbed incoming atmospheric radiation.

Existing radiative cooling techniques are classified as Passive or Hybrid. Passive systems, mainly involve the use of the building roof as the radiative component, while hybrid systems involve the use of special metallic surfaces characterized by high emissivity in the longwave range.

Painting the roof white increases the reflectivity of the roof to solar radiation

thus reducing its temperature. Measurements of the performance of this technique reported in (98) give a cooling potential of 0.014 KWH per square meter per day. Similar results are also reported in (99). However, the effect of color is more important with light structures than with structures of high thermal capacity.

Exposing the cold mass to the sky during the night while protecting it during the day by a movable insulation is another passive radiative cooling techique which tries to optimise the potential of radiative cooling. Measurements of the performance of this technique reported in (98) give a cooling potential of 0.266 KWH per square meter per day.

The Skytherm system which is proposed by H. Hay involves the use of water bags which are placed on the roof. A movable insulation is placed above the bags during the day to keep the solar heat away from the water and is removed during night when the water losses heat by convection, radiation and evaporation and thus the water cools the living spaces. Various other types of architectural integration of this system are reported in (100). Knowledge on this system comes from monitoring of the Hay's house at Atascadero in California, (101). It was observed that on a typical summer day, the variation in outdoor temperature was from 13 to 34°C, while the corresponding indoor temperature ranged from 21 to 23°C only.

The main limitation associated with passive radiative techniques is that they are more effective only in single storey buildings or the upper floor of multistorey buildings. Specific problems with the above presented techniques are discussed in (4).

Hybrid radiative cooling systems involve the use of specialized metallic longwave radiators which can reach temperatures below those achieved when the roof is cooled directly. The operation of the system involves the flow of a transfer medium, water or air, flowing above, under or within the radiator which is cooled and then is used to cool the building.

The cooling potential of the metallic radiators for some European locations is discussed in (4, 102). It is found that under stagnation and for mean climatic conditions, the expected temperature depression rarely exceeds 3°C. Under optimum climatic conditions, the calculated maximum depression temperature range from 5 to 7°C.

Use of selective surfaces as well as windscreens transparent to infrared radiation can, under certain conditions, improve the performance of the metallic radiators.

Experiments with selective surfaces described in (103–107), report temperature's depression from 5 to 17°C. Comparisons with ordinary surfaces have shown however that the difference between them is negligible. Also when the temperature depression is important, condensation occurs on the surface and thus the surface losses its selective radiative properties.

Experiments using windscreens, described in (108), report that a radiator covered by a windscreen was 3–4°C lower than the corresponding temperature of an ordinary radiator. However when the temperature of the polyethylene film drops below the ambient dew point, dew is formatted over the windscreen, and thus the transmissivity of the polyethylene to the infrared radiation is reduced significantly.

5 INHABITANT ACTIVITIES

Seasonal and diurnal migration as well as appropriate clothing and metabolism control are the most important cooling strategies related to inhabitant activities.

Migration is the most elementary cooling strategy. Humans move away physically from discomfort towards comfort. Migration can be seasonal or diurnal (109). Seasonal migration involving moving to summer cottages, where cluster is more favourable. Diurnal migration is related to the domestic flexibility which permits moving to the most comfortable building zone or outside the building. This practice that implies redundancy in architectural accommodation and a certain variety of quality for similar activities, is a prevalent strategy in overheated climates.

Clothing in warm climates is light and should cover more skin area in order to reduce, by shielding, the incoming solar radiation. Also clothing should encourage vapour permeability in order to enhance evaporative benefits from sweat and perspiration.

Control of the metabolic rate using lighter food, less animal fats and more fluids, can be useful as the deep temperature and the heat production of the body is modified to some degree.

Finally reduction of the metabolic rate is achieved by reducing the physical activity or by scheduling the high activities at cooler times of the day.

6 DESIGN TOOLS FOR PASSIVE AND HYBRID COOLING

Use of passive and hybrid techniques and components for space cooling requires appropriate sizing of the systems. Design or computational tools for passive solar buildings are widely developed, distributed and used, however most of those tools are designed for passive heating purposes and cannot be used to simulate the summer performance of the buildings.

In order to identify the design and computational tools available for passive and hybrid cooling purposes, an extensive survey of the existing tools has been performed.

The information collected is classified in a data base, (1). The applicability and the usefulness of the tools is examined using seven groups of criteria as below, (110):

—Capabilities of the tool regarding the various aspects of the building cooling.
—Required computer system.
—Required professional background.
—Phase of the building design for which the tool is suitable.
—Completeness of the buildings performance description.
—Building type applicability and
—Calculation method used.

The calculation capabilities of the tools regarding the various aspects of the cooling are analyzed according to the following parameters:

—Evaluation of the building cooling load.
—Calculation of the internal air temperature.
—Calculation of the impact of thermal mass to the building.
—Calculation of the impact of shading to the building.
—Calculation of the performance of ventilation techniques and
—Calculation of the performance of the environmental heat sinks based systems, (Evaporative, Ground, Radiative)

It is found that one hundred twenty eight, 128, programs have some capabilities to calculate the cooling load of a building. However only 54 among them can also calculate the variation of the internal air temperature and only 45 can also take into account the impact of mass and shading. Finally, there are only 23 programs which can also simulate the natural ventilation strategies.

From the above programs, 8 of them are designed for mainframe computers and are used especially for research purposes. Nine programs are designed for personal computers, and four tools are suitable for various type of microcomputers.

Regarding the design tools available to simulate the use of environmental heat sink techniques, 22 tools managing the convective cooling techniques have been identified. Also there are 3 tools which are capable to simulate evaporative techniques, 2 for radiative cooling and 19 for ground cooling.

Most of the programs are written for architects and engineers. There are 113 programs suitable for architects, 123 programs for engineers, 55 programs for technicians, 28 programs for researchers and 42 programs for builders. The majority of the programs can be used for residential and small commercial buildings. Fifty five of the tools are suitable for the predesign phase, fifty five for the schematic design phase, fifty two for the design development, twenty one for post design services and sixteen tools can be used for research purposes.

For the large commercial buildings there are 26 programs suitable for the predesign phase, 39 for the schematic design phase, 47 for the design development, 16 for post design and 11 for research purposes.

Almost all the programs which can treat cooling problems, 123, can be used also for heating purposes, however only 48 tools include daylighting subroutines. From these 41 are suitable for architects, 44 for engineers, 13 for technicians and 14 for builders. Also 24 are written for mainframe computers, 34 for microcomputers and 2 are manual methods.

In conclusion there is a number of design tool available for calculating the cooling energy requirements. However there are a few tools available for calculating the cooling load modulation due to mass and shading. There is a number of tools available for calculating the effects of ventilation in buildings. Most of these tools consider cross ventilation and few of them consider chimney effect ventilation techniques. However, there is a lack of tools for calculating the performance of components and techniques based on the use of environmental heat sinks.

Finally, it should be pointed that, very little information is available on the validation of the tools except for some international and national sponsored design tools.

7 EXAMPLES OF PROJECTS

Climatic conditions in Southern Europe require the consideration of basic passive cooling techniques, during the overall architectural design. Shading techniques and components, massive constructions and natural ventilation techniques are traditionally found in Mediterranean architecture (111–112).

Progressive in passive and hybrid cooling during the last years, and increased electricity cost, have promoted integration of the new cooling systems in building design. Consequently, a number of demonstration buildings, using modern passive and hybrid cooling techniques and components have been designed and constructed.

Thirteen of these buildings covering all the South region of Europe have been extensively analyzed and presented in separate brochures (1). Five of the buildings are educational centers, four are hotels and holiday complexes and the rest are for residential and commercial use. The location of each project as well as the basic climatological data for each site are given in Table 1. Also architectural and operational information is given in Table 2.

All the buildings have been designed taking into account the basic principles of passive cooling. Therefore all the buildings are highly insulated, are characterized by increased thermal mass and very efficient shading devices are used.

For all the educational buildings, the main design principle was to use the courtyard as a buffer space, functionally utilized as corridors, resting and living areas. The design and the control of this courtyard depends on the microclimate and, the building in Ioannina and Guillena, which are located in continental zones, have this buffer space closed and very well protected against sun in summer and cold in winter, whilst the building in Almeria and Los Molinos, located near the sea, have an open courtyard which only protects from the sun in summer, taking into account the mild winter temperatures.

For most of the thirteen buildings, ventilation is the most important heat dissipation technique, using wind and stack effect techniques. Also, almost all of them use cooling systems based on environmental heat sinks like, evaporative, radiative and ground coupling techniques. More information on each building can be found in (1) or in the corresponding references given in Table 1.

Regarding the thermal performance of the buildings we should point out that only 8 projects are monitored or are under monitoring. The measured and predicted performance of the building shows that the passive and hybrid cooling systems cover a high percentage of the needs, which varies from 40 to 100 percent, Table 1.

Finally the cost of the buildings, given also in Table 1, is very close to the cost of conventional buildings, showing that applications of passive and hybrid cooling techniques and components does not affect considerably the cost of the buildings.

Table 1. Buildings using passive and hybrid cooling techniques. Basic data.

Building name	*Country*	*Latitude*	*Solar radiation*	*Reference*	*Performance–coverage percentage*	*Monitoring*	*Cost*	*ECUS/m²*
1. School in Almeria	Spain	36, 0	6100 MJ/m²	(1)	100 (Predicted)	YES	199	(1984)
2. School in Guillena	Spain	37, 0	5914	(1)	89 (Predicted)	YES	255	(1987)
3. School in Crato	Portugal	39, 15	—	(1)	Not Available	NO	231	(1984)
4. Philosophical School	Greece	39, 42	3805	(115)	70 (Predicted)	YES	Not Available	
5. Los Morinos School	Spain	38, 25	4524	(1)	Not Available	YES	574	(1984)
6. Archilohos Touristic Complex	Greece	37, 00	4511	(1)	60 (Predicted)	NO	790	(1988)
7. Eragiadakis Touristic Appartments	Greece	35, 5	4514	(116)	Not Available	NO	Not Available	
8. Helas Holidays Hotels	Greece	35, 0	4482	(117)	52 (Predicted)	NO	778	(1980)
9. Holiday Complex Gournes	Greece	35, 4	4514	(118)	40 (Predicted)	NO	1000	(1988)
10. Marathon Residential Building	Greece	38, 5	4374	(119)	60 (Predicted)	YES	Not Available	
11. Residential House	Portugal	33, 0	—	(1)	100	YES	445	(1988)
12. Office Building	Portugal	33, 0	—	(1)	100	YES	480	(1984)
13. Bioclimatic Rotunda	Spain	37, 25	4215	(1)	—	YES	379	(1988)

Table 2. Buildings using passive and hybrid cooling techniques. Geometrical and occupany data.

Building	*Floor Area* (m^2)	*Volume* (m^2)	*Occupancy date*	*Number of Occupants*	*Operating hours*	*Operating period*
1. School in Almeria	2071	3452	1987	400	9–1.30, 15–17.30	Sept–June
2. School in Guillena	1832	6668	1987	400	9–1.30, 15–17.30	Sept–June
3. School in Crato	3200	—	1988	420	8.30–17.30	Sept–June
4. Philosophical School	4800	—	1990	>100	8.00–19.00	All year
5. Los Molinos School	330	1253	1985	—	9–1.30, 15–17.30	Sept–June
6. Archilohos Complex	1200	4200	Undr. Construction	40	All day	Summer
7. Fragiadakis Apprts	1005	2920	Undr. Construction	>50	All day	Summer
8. Hellas Holiday Hotels	21859	100514	Undr. Construction	600	All day	Summer
9. Holiday Complex Gournes	400	1200	Undr. Construction	30	All day	Summer
10. Residential Building	362	1437	1979	4	All day	All year
11. Residential House	103	498	1988	2	All day	All year
12. Office Building	123	518	1985	3–8	Variable	All year
13. Bioclimatic Rotunda	1600	9600	1988	100 persons/h	8–24h	All year

8. RESEARCH NEEDS

It is widely accepted that overheating of buildings is the most important enery and comfort problem in the Southern Countries. Also the systems used for cooling of buildings led to unnecessary high energy consumption and sometimes to inferior air quality (113).

Research, Development and Demonstration projects for better cooling of buildings must therefore have as prime goals to:

(a) Decrease electrical use for A/C and increase energy efficiency.

(b) Increase thermal comfort and indoor air quality.

(c) Protect environment.

The technology areas where research should be concentrated in order to meet the above goals are

(a) Cooling load estimation methods and A/C sizing techniques.

(b) Passive and Hybrid cooling techniques and components.

(c) Load shifting technologies.

(d) CFC's substitution technologies and

(e) High efficiency heat pump technologies.

Comparison of predicted and measured cooling load of buildings, (114), have shown that the predicted cooling loads are significantly higher than the actual measured cooling loads. This lead to an important oversizing of the used A/C system and considerably increase the energy consumption. Therefore, as a first step the quality of the climatic input needs should be more realistic alike new accurate computer tools, for the calculation of the cooling load should be developed and validated.

To improve knowledge and possibilities for application of Passive and Hybrid Cooling technologies, scientific research should be developed primarily on the three following areas:

(a) Solar Control and heat attenuation.

(b) Passive heat removal techniques and use of environmental heat sinks.

(c) Interaction between building and environment.

Research should be directed towards:

(a) The better knowledge of the effects of mass, ventilation, building shape, shading and microclimate, for free floating and air conditioned buildings.

(b) The development of new efficient cooling components like evaporative coolers, radiative collectors etc.

(c) The development of new products for the building envelope like the thermochromic and electrochromic glasses, transparent insulation etc.

(d) The collection and classification of the relevant climatological data.

(e) The development of validated tools for the calculation of the performance of passive cooling techniques and components.

9 CONCLUSIONS

Demand for indoor cooling has increased rapidly over the past few years, creating important environmental, health, capital and mainly peak electricity load problems.

Passive and Hybrid cooling techniques and components can minimize the use of mechanical energy and its impact on the environment and on occupant health, while they can decrease significantly peak electric demand.

Important knowledge on the topic has been produced during the last years and demonstration buildings designed using passive and hybrid cooling systems, present a significant energy performance and excellent indoor comfort conditions. However the impact on professional building design practice has been modest.

Important future research actions are necessary in order to increase our knowledge base on the topic. Also an important effort should be made in order to increase the accessibility of the existing and new information.

Acknowledgments

This work has been financed by the E.E.C. Research Project B.2000. The authors would like to thank Prof. C. den Ouden, Coordinator of the Project as well as the Commission of the European Communities, D.G. 12, for their financial support. Also the authors would like to thank Dr K. Balaras for his assistance during the preparation of this paper.

References

1. M. Antinucci, B. Fleury, J. Lopez, D. Asiain, E. Maldonado, M. Santamouris, A. Tombazis and S. Yannas, "Horizontal Study on Passive Cooling", M. Santamouris (ed), B.2000 Research Program, D.G.12, E.E.C., 1990.
2. Predicasts Inc., Predicasts Forecasts, Issue 108, 4th Quarter, Refrigeration and Air Conditioning Equipment Data, 1987.
3. United Nations, International Trade Statistics Yearbook, Vol III, Trade by Commodity, 1980–1985.
4. M. Santamouris, Natural Cooling Techniques. Proc. Workshop on Passive Cooling. E. Aranovich, E. Oliveira Fernandes and T. C. Steemers (eds). Ispra, Italy 2-4 April 1990.
5. C. J. Andrews, *The Energy Journal* **4,** 1, 79, 1987.
6. M. Santamouris *et al.*, Correlations of peak electricity profiles with some climatological indices. Greek Productivity Center, Athens, 1991.
7. A. Hedge, E. M. Sterling and T. D. Sterling, Building indices based on questionnaire responses. Proc IAQ 86, ASH-RAE, pp. 31–43, Atlanta, USA, 1986.
8. M. Santamouris, E. Daskalaki, D. Kitari, K. Kostopoulos and V. Papadimitriou: A comparative study on the air quality of office buildings. Greek Productivity Center, Athens, 1991.
9. PROTECHNA Ltd, Passive and Hybrid Cooling in Greece. Study carried out for the Center for Renewable Energy Sources, Greece, Athens, 1991.
10. Z. Warsi and I. Chand, *Indian Journal of Technology,* **6,** 1, 23–25, 1968.
11. M. Girgis, Landscaping for energy conservation. Florida Solar Energy Center, EN, 12, 1983.
12. H. Taha, H. Akbari and A. Rosenfeld, Vegetation canopy microclimate. A field project in Davis. California LBL Report 24593, 1988.
13. D. A. Montgomery, *Passive Solar Journal,* **4,** 1, 79, 1987.
14. S. Risvi and K. Talib, Landscape as energy and environmental conservation in the arid regions Saudi Arabi. Proc. International Conf. Passive and Hybrid Cooling. Miami Beach, 1981.
15. R. Stirling, J. Carmody and G. Elnicky, Earth sheltered community design, Energy efficient residential development. N.Y. Van Nostrant Reinhold Company, 1981.
16. G. Robinette, *Landscape Planning for Energy Conservation,* Reston, VA, Environmental design Press, 1977.

17. A. Bowen, Heating and cooling of buildings of sites through landscape planning. Passive Cooling Handbook. Newark DE/AS/ISES, 1980.
18. E. Duckworth and J. Sandberg, Bulletin of Meteorological Society, 1954.
19. L. Gold, *Canadian Journal of Earth Science,* **4,** 199, 1967.
20. H. Taha, H. Akbari, A. Rosenfeld and J. Huang, Residential cooling loads and the urban heat island. The effect of albedo. LBL Report 24008, 1988.
21. A. Moffat and M. Schiller, *Landscape Design Hot Save Energy,* N. Y. William Norrow and Company, 1981.
22. J. Y. Yellot, Passive and Hybrid Cooling Research. *Advances in Solar Energy,* 1983.
23. I. Chand and K. Krishak, Civil Engineering Construction and Public Works Journal, July 1971.
24. I. Chand, Civil Engineering Construction and Public Works Journal, Nov. 1973.
25. S. Yannas, Solar Control Techniques, Ibid 4, 75–97, 1990.
26. V. and A. Olgay, *Solar Control and Shading Devices.* Princeton UP. 1967.
27. E. Mazria, *The Passive Solar Energy Book.* Rodale Press. 1979.
28. P. Achard and R. Gicquel, European Passive Solar Handbook. Basic Principles and Concepts for Passive Solar Architecture. Commission of the European Communities. 1986.
29. E. Shaviv, A design tool for determining the form of fixed and movable sunshades. ASHRAE Transactions, 1984.
30. N. Billington, *Building Physics: Heat.* Pergamon Press, London, 1967.
31. J. Anquez, M. Croiset and J. Le Quere, Calcul simplifie des economies de chauffage apportees par l energie solaire. CSTB, Cahier 1704, Paris, 1981.
32. E. Shaviv, On the determination of the optimum thermal mass in the Mediterranean climate. Proc. PLEA 88, E. de Oliveira Fernandes and S. Yannas (eds). Porto, Pergamon Press.
33. G. Lefebvre, I. Blanc Sommereux, Analysis of building Inertia using a modal description, Ibidem.
34. A. Guglielmini, The relative merits of envelope and interior structures on the weekly thermal inertia of buildings, Ibidem.
35. J. D. Balcomb and R. W. Jones, Workbook for Workshop on advanced passive solar design. Passive Solar Architecture Conference, Bled, Jugoslavia, 1988.
36. J. A. Clarke, The impact of alternative constructions. ABACUS Occasional paper, University of Strathclyde, Glasgow, U.K., 1980.
37. M. J. Brown, Integration of thermal mass heat storage in commercial building design. Proc. ASH-RAE/DOE/BTEC Conf. Thermal performance of the exterior envelopes of buildings III, 1985.
38. S. J. Byrne and R. L. Ritschard, A parametric analysis of thermal mass in residential buildings. Ibidem.
39. M. E. Hoffman and M. Feldman, *Building and Environment,* 1981.
40. G. Paparsenos, Heat attenuation and the thermal mass effect. Ibid 4, 111–119.
41. M. Antinucci, Heat attenuation as a mean to limit cooling load and improve comfort. Ibid 4, 101–110.
42. C. N. R., Repertorio delle caratteristiche termofisiche dei componenti edilizi opachi e transparenti. Edizioni CNR-PFE, 1982.
43. E. Athanassakos and E. Gratsia, Suitability of building materials for passive solar applications. Report I. Institute for Technological Applications, Greek Productivity Center, 1988.
44. M. J. Brown, *J. of Solar Energy Engineering,* **112,** 273–279, 1990.
45. I. Chand, *Architectural Science Review,* **130–133,** 1970.
46. H. J. Sobin, Analysis of wind tunnel data on naturally ventilated models. Appendix A: Test Data Catalog. Tucson AZ, 1983.
47. T. Boutet, *Controlling Air Movement.* McGraw Hill Company 1987.
48. S. Chandra, P. Fairey and M. Houston, Cooling with ventilation, F.S.E.C., SERI Report Sp. 273–296, Dec 1986.
49. B. Fleury, Ventilative Cooling. State of the art. Ibid 4, 1990. 45. I. Chand, Architectural Science Review, 130–133, 1970.
50. M. Bahadori, A Passive cooling heating system for hot arid regions. Proc. 13th National Passive Solar Conference, Cambridge, USA, 364–367, June 1988.
51. C. Karakatsanis, M. Bahadori and B. Vickery, *Solar Energy* **37,** 5, 363–374, 1986.
52. A. Bouchair, D. Fitzgerald and J. Tinker, Moving air, using stored solar energy. Proc. American Solar Energy Conference, Cambridge, 1988.
53. P. Koronakis, Submitted to *Int. J. Solar Energy,* 1991.

54. A. Dimoudi, An evaluation of the use of solar chimneys to promote the Natural ventilation of buildings. MSc. Thesis, Cranfield Institute of Technology, Sept. 1989.
55. B. Givoni, Ventilation problems in hot countries. Research report to Ford Foundation. Haifa, Israel, Building Research Station, Israel Institute of Technology, 1968.
56. S. Chandra, P. Fairey, M. Houston and A. Kerestecioglu, Wingwalls to improve natural ventilation: Full scale results and design strategies. Florida Solar Energy Center, PF-47-83, 1983.
57. I. Chand, V. Sharma and N. Krishak, *Indian Journal of Technology* **15,** 369–374, 1977.
58. M. Santamouris and E. Daskalaki, Performance of nighttime ventilation of buildings in Greece. Report for the Greek Productivity Center, 1991.
59. S. Baer, Cooling with night air. Albuquerque, NM, Zomeworks, 1984.
60. M. E. Hoffman and M. Gideon, Window design practical directions for passive heating and cooling in heavy and light buildings. Proc. Windows in building design and maintenance, 277–288, Goteborg, Sweden, 1984.
61. N. V. Baker, Passive cooling evaluation method – PACE. Proc. PLEA 86. Pecs, Hungary, 1986.
62. I. Chand, *Research and Industry,* **18,** 3, 50–53, June, 1973.
63. S. Chandra, Fans to reduce cooling costs in the Southeast. Florida Solar Energy Center, EN-13-85, 1985.
64. H. Wu, The use of oscillating fans to extend the summer comfort envelope in hot, arid climates. ASHRAE Far East Conference on Air Conditioning in Hot Climates. Malaysia, Oct. 1989.
65. D. Scheatzle, H. Wu and J. Yellot, Extending the summer comfort envelope with ceiling fans in hot arid climates. ASHRAE Transactions, V. 95, 1, 1989.
66. W. A. Cunningham and T. L. Thompson, Passive Cooling with Natural draft cooling towers in combination with Solar Chimneys. Ibid 61, 1986.
67. G. M. Mignon, W. A. Cunningham and T. L. Thompson, Passive Cooling with Solar updraft and evaporative downdraft chimneys. Interim report for work performed 6/15/84 to 3/1/85 under U.S. Department of Energy. Contract No E-FG02-84CH10205, ERL, Univ. of Arizona, 1985.
68. D. W. Abrams: *Low Energy Cooling.* Van Nostrand Reinhold Co, 1986.
69. H. R. Hay and I. J. Yellot, ASHRAE Trans. **75,** 1969.
70. S. P. Jain and K. R. Rao, *Building Science* **9,** 9, 1974.
71. A. L. Pittinger, W. R. White and K. I. Yellot, Proc. Sec. Nat. Passive Solar Conference AS/ISES, 773, Philadelphia, 1978.
72. M. S. Sodha, A. K. Khatry and M. A. S. Malik, *Solar Energy* **20,** 189, 1978.
73. M. S. Sodha, A. Kumar, A. Singh and G. N. Tiwari, *Building Environment,* **15,** 133, 1980.
74. J. Watt, *Passive Solar Journal,* **4,** 3, 293, 1987.
75. D. Pescod and R. K. Prudhoe, *Telecommunications Journal Australia,* **30,** 2, 1980.
76. B. Givoni and L. Katz, *Energy and Buildings,* **8,** 15, 1985.
77. F. Hazer, Proc. Conf. The use of earth covered buildings. F. Moreland (ed), US GPO 038-000-00286-4, 21–36, 1975.
78. R. Cole and R. Kennedy, 5th NPSC, J. Hyes and R. Snyder, (eds), AS/ISES, Newark, Delaware, pp. 704–706, 1980.
79. S. Baggs, Underground utilization, a reference manual of selected works. T. Stauffer, (ed), pp. 573–599, 1978.
80. O. Newman, CIAM 59, Alec Tiranti, Ltd, 1961.
81. C. Carmody, G. D. Meixel, K. Labs and L. S. Shen, *Advances in Solar Energy,* **2,** 297, 1985.
82. E. Chronaki, Ph.D. Thesis, University of Thessaloniki, 1983.
83. D. Carter, *Underground Space* **1,** 317–323.
84. W. J. Rivers, B. Helm, W. D. Warde and W. Grondzik, Ibid **14,** 126, 1981.
85. A. Fanciotti and G. Scudo, Ibid **14,** 179, 1981.
86. B. B. Saini, Building Environment, *An Illustrated Analysis of Problems in Hot Dry Lands.* Angus and Robertson, Sydney, 1973.
87. M. Bahadori, *Scientific American* **238,** 144–154, 1978.
88. M. Santamouris, DEA Report, I.N.P. Grenoble, 1981.
89. C. E. Fransis, Ibid **14,** 1981.
90. J. Claeson and A. Dunand, Heat extraction from the ground by horizontal pipes. Swedish Council for Building Research, D1, 1983.
91. A. L. T. Seroa da Motta and A. N. Young, Proc. INTERSOL 85, E. Bilgen and K. G. T. Hollands (eds), p. 759, 1985.

92. G. Schiller, M.Sc. Report, L.B.L. 1982.
93. W. Abrams, C. Donald and C. C. Benton, Proc. of the 5th National Passive Solar Conference AS/ISES, Amherst, 1980.
94. A. S. Dhaliwal and D. Y. Goswavi, Proc. of the 6th Annual ASME Solar Energy Conference, ASME, 1984.
95. C. Nordham and B. Douglas, Proc. of 4th National Passive Solar Conference, Kansas City, 1979.
96. N. Santamouris, Report on the SE/205/85 Energy Demonstration Project, D.G. 17, EEC, 1989.
97. A. Tzaferis and D. Liparakis, A comparative study of the algorithms predicting the performance of earth to air heat exchangers. Interim Report, TEI Pirea, Greece.
98. B. Givoni. Ibid 14, 279, 1981.
99. B. Givoni and M. Hoffman, *Build. International* **6,** 525.
100. K. L. Haggard, *Solar Energy,* **19,** 403, 1977.
101. H. Hay, Proc. Conference Passive Solar Heating and Cooling, Albuquerque, N.M. 1976.
102. A. Argyriou and M. Santamouris, Possibilities of radiative cooling in Greece. Proc. Conf. Energy and Environment. A. Sayigh (ed), Reading, 1990. Pergamon Press.
103. J. T. Pytlinski, G. R. Conrad and H. L. Connell, *Alternative Energy Sources,* 101, N. Veziroglou (ed), 1983.
104. F. Sakkai, 5th NPSC, J. Hyes and R. Snyder (eds), AS/ISES, Newark, Delaware, 483, 1979.
105. W. C. Miller and J. O. Badley, Ibid 104, 480, 1979.
106. S. Catalonotti *et al., Solar Energy* **17,** 83, 1975.
107. B. Landro and P. G. McCormick, *Int. Heat Mass Transfer* **23,** 613, 1980.
108. M. Mostrel and B. Givoni, *Passive Solar Journal,* **1,** 4, 229, 1982.
109. J. Cook, Cooling as the absence of heat. Strategies for the prevention of thermal gain. Ibid **14,** 612, 1981.
110. I.E.A., *Design Tool Survey,* 1987.
111. Maria Argyropoulos, Thalis Argyropoulos and Simos Yannas: Country Regional Monograph. Greece. Ibid **14,** 867, 1981.
112. J. Bouillot, The bioclimatic domestic space components. Variations of their architectural translations on the periphery of the Mediterranean sea. Proc. PLEA 88, E. de Oliveira Fernandes and S. Yannas (eds), 47, 1988. Pergamon Press.
113. J. V. Anderson (ed): Air Quality, Heating and Cooling of Buildings. Final Report on IEA Workshop, Gothenburg, September 12–14, 1988.
114. J. D. Balcomb, *Integration of Heating, Cooling and Daylighting.* Ibid **112,** 567, 1988.
115. E. Stournas-Triantis, M. Santamouris and T. Metsis, Passive Solar Restoration of the new School of Philosophy building in the University of Ioannina, Greece. Proc. International Climatic Architecture Congress, 96, Louvain La Neuve, 1986.
116. P. Koronakis, Y. Kalligeris and M. Santamouris, The contribution of appropriate energy design strategies and appraisal of a touristic residence complex in Crete. Proc. Second European Conference on Architecture, A. Lohr (ed), Pris, 1989.
117. A. Tombazis, A. Argiriou and M. Santamouris, *Int. J. Solar Energy,* **9,** 1–12, 1990.
118. E. Athanassakos, M. Kopidakis and C. Thofylaktos, Passive Cooling of a holiday complex in Iraklion, Crete, Greece. Proc. Conf. Clean and Safe Energy Forever, H. Horigome, K. Kimura, T. Takakura, T. Nishimo and I. Fujii (eds), pp. 1149–1152, 1989. Pergamon Press.
119. V. Bouriotis, M. Santamouris and C. Lefas, Heating and cooling of a remote manufacturing unit coupled by the living spaces using passive solar technology. Proc. European Conference on Architecture, pp. 127–130, Munich 1987.