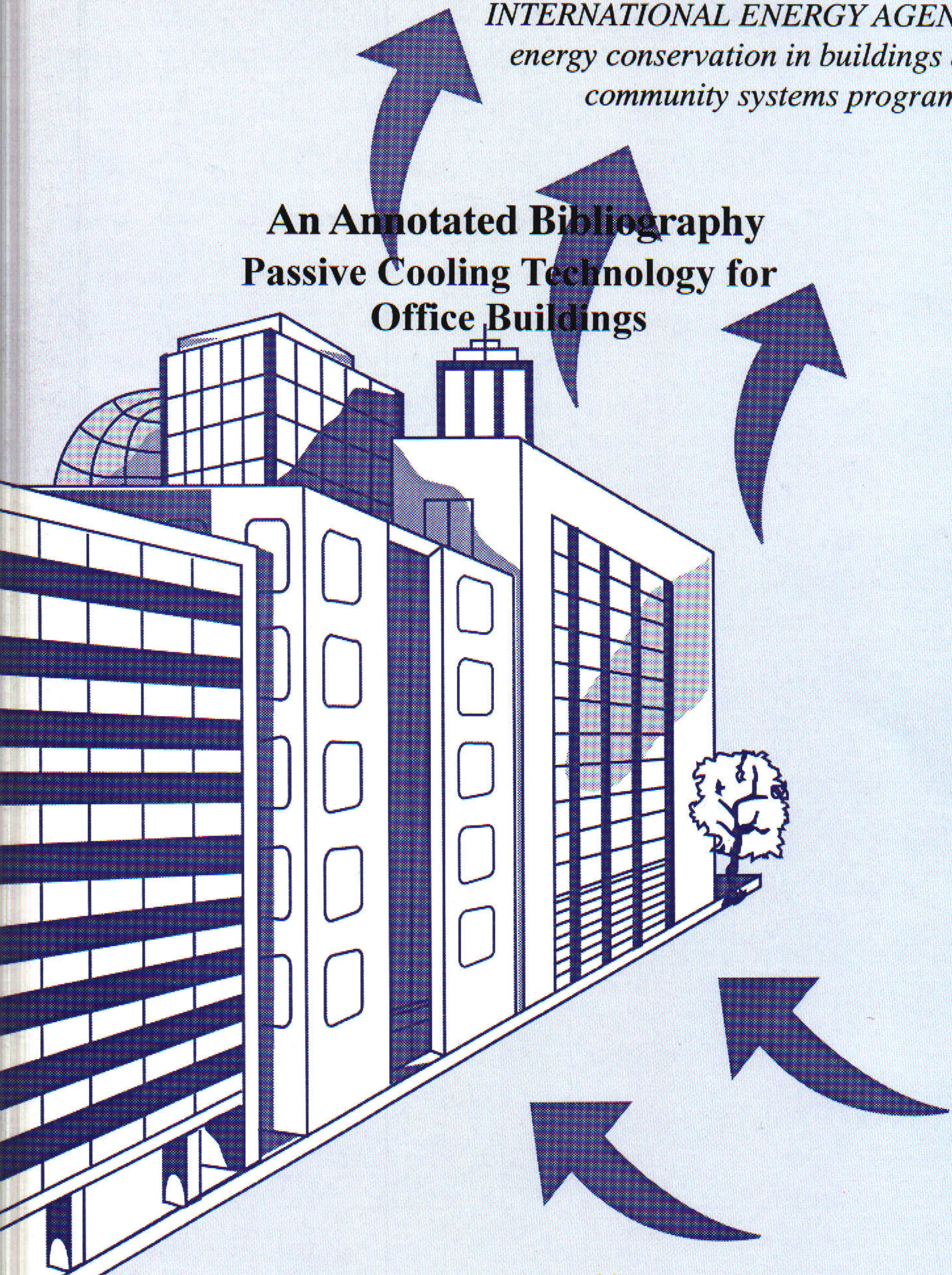
INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and
community systems programme

An Annotated Bibliography
Passive Cooling Technology for Office Buildings



Air Infiltration and Ventilation Centre
University of Warwick Science park,
Sovereign Court,
Sir William Lyons Road,
Coventry CV4 7EZ,
England.

Passive Cooling Technology for Office Buildings
An Annotated Bibliography

Mark J. Limb

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (completed projects are identified by *):

I	Load Energy Determination of Buildings*
II	Ekistics and Advanced Community Energy Systems*
III	Energy Conservation in Residential Buildings*
IV	Glasgow Commercial Building Monitoring*
V	Air Infiltration and Ventilation Centre
VI	Energy Systems and Design of Communities*
VII	Local Government Energy Planning*
VIII	Inhabitant Behaviour with Regard to Ventilation*
IX	Minimum Ventilation Rates*
X	Building HVAC Systems Simulation*
XI	Energy Auditing*
XII	Windows and Fenestration*
XIII	Energy Management in Hospitals*
XIV	Condensation*
XV	Energy Efficiency in Schools*
XVI	BEMS - 1: Energy Management Procedures*
XVII	BEMS - 2: Evaluation and Emulation Techniques*
XVIII	Demand Controlled Ventilating Systems*
XIX	Low Slope Roof Systems*
XX	Air Flow Patterns within Buildings*
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XXII	Energy Efficient Communities*
XXIII	Multizone Air Flow Modelling (COMIS)*
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XXV	Real Time HEVAC Simulation*
XXVI	Energy Efficient Ventilation of Large Enclosures*
XXVII	Evaluation and Demonstration of Domestic Ventilation Systems
XXVIII	Low Energy Cooling Systems
XXIX	Daylight in Buildings
XXX	Bringing Simulation to Application
XXXI	Energy Related Environmental Impact of Buildings
XXXII	Integral Building Envelope Performance Assessment
XXXIII	Advanced Local Energy Planning
XXXIV	Computer-aided Evaluation of HVAC System Performance
XXXV	Design of Energy Efficient Hybrid Ventilation (HYBVENT)

Annex V Air Infiltration and Ventilation Centre

The Air Infiltration and Ventilation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Canada, Denmark, Finland, France, Germany, Greece, Netherlands, New Zealand, Norway, Sweden, United Kingdom and the United States of America.

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Other Bibliographies in this series:

Ventilation and Infiltration Characteristics of Liftshafts and Stairwells;
Air Intake Positioning to Avoid Contamination of Ventilation Air;
Ventilation in Schools;
Garage Ventilation;
Natural Ventilation;
Heat Pumps for Ventilation Exhaust Air Heat Recovery;
Ventilation and Acoustics.

This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme.

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Annex V

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Additional copies of this report may be obtained from

The Air Infiltration and Ventilation Centre
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Great Britain

Scope

This bibliography is aimed at researchers, designers and engineers who are seeking an overview of current developments into passive ventilation technologies within office buildings and their impact on current ventilation practices. References quoted in this document are taken from the AIVC's bibliographic database, AIRBASE and, subject to copyright restrictions are available to organisations in AIVC participating countries through the Centre's library service.

1.0 Introduction

Changes in building style and function have led to a greater dependence on artificial forms of lighting, heating, cooling and ventilation within modern buildings. Recent environmental concerns have however, led to a greater focus on traditional passive methods of solar control and natural lighting and renewed enthusiasm for natural ventilation and passive cooling methods. Designers, architects and engineers have adapted many traditional basic principles to fit in with the modern office environment, both in terms of building practices and materials and in the way in which we work today, often resulting in innovative design solutions. Several authors have examined the state of the art with regards to passive cooling systems and technologies, including Antinucci et al (1989, #11156), (1992, #10958), (1990, #10888) Frangoudakis (1990, #10884), Santamouris (1990, #10879), Santamouris et al (1997, #9838) Santamouris and Asimakopolous (1996, 10678), Dominguez (1990, 10881), Gallo (1996, #9982) (1994, #8381), Agas et al (1991, #10906), and Liveris (ed) (1994, #9033).

All of these authors discuss the historical perspective of passive cooling and how it has been adapted for use in modern buildings with much success in hot climates. They also discuss the importance of building form, shading, location construction materials and climate. Dominguez (1990, #10881) on the other hand focuses more on future research in this field, and highlights the main obstacles and faults which exist in the current research (1990) and looks at the measures the author feels should be implemented to overcome these problems. Wouters (1990, #10882) discusses how monitoring activities can be best adapted to the study of passively cooled buildings. The paper outlines the experimental equipment needed for such passive cooling studies, including the PASSYS test cell, and highlights a number of points regarding the interpretation of results, including the reliability of any modelling tools and due care with regards to any error analysis. Liveris (1994, #9033) undertakes a study of passive and low energy cooling in buildings for the European THERMIE project. The maxibrochure outlines the main considerations of low energy and passive cooling and discusses the best ways in which these can be achieved. The report concludes with a number of case study buildings taken from Europe and America, which show how these technologies have been employed in real buildings, such as the EXPO'92 building in Seville, Spain (also Velazquez et al 1992, #6267) and The Business Promotion Centre in Germany. Santamouris et al (1997, #9838). outlines a European supported project called AIOLOS. Being partly financed within the framework of ALTENER, it aims to create and disseminate educational material on the use of passive ventilation cooling systems and techniques. Material includes, case studies, slides, guidebooks, technical manuals and didactic software.

Another initiative is the International Energy Agency's ECBCS Annex 28 which was established to examine the number of alternative cooling strategies and systems that could lead to a reduction in energy consumption in the field of cooling. The results of this investigation have been documented by Irving and Concannon (1993, #11152), Jaunzens and Wylds (1994, #8292) and more recently as an IEA Annex report entitled "Review of Low Energy Cooling Technologies"

(1995) and Millet (1997, #10593). The report reviews the 1995 status of these technologies including night ventilation, ground cooling with air, slab cooling with air, desiccant cooling, evaporative cooling, slab cooling with water, chilled ceilings and ground cooling with water using aquifers. Millet (1997, #10593), outlines a number of detailed tools and guidance notes created to help designers formulate and integrate cooling systems into buildings that until now have been traditionally mechanically cooled. Irving (1996, #10261) outlines the role of ventilation in cooling non domestic buildings, setting out details for maintaining comfort as well as briefly discussing a wide variety of ventilation and cooling strategies. Irving concludes by stating that good design must seek to optimise the ventilation system design and control strategy to provide comfort in an efficient way.

However, passive cooling technologies can only be economically employed in certain geographic locations and in certain building types. For example Santamouris and Argiriou (1994, #8276) monitored the energy consumption of 1000 public and commercial buildings in Greece Their figures show that over half of the total energy consumption is used for heating and is derived from fossil based fuels, whilst 12% of the total energy consumption is used for cooling and is achieved by electricity. Potential therefore exists for primary energy savings related to cooling in Greece. Ogoli (1994, #8667) also briefly makes the case for passive cooled non domestic buildings in Kenya. He outlines the erratic supply and high cost of electricity in his country as well as the wide variety of climatic conditions which pose great challenges to designers who wish to exploit this technology, although the high level of daylight also provides advantages. The most common methods used in Kenya for the protection of heat gains a include one, or a combination, of solar control and shading of building surfaces, thermal insulation and use of thermal mass, building form layout and use of external finishes, landscaping and use of outdoor and semi outdoor spaces and the control of internal heat gains. Although despite these factors, passive cooling in Kenyan non domestic buildings is still not as popular as in domestic ones, the author believes that such technology is possible and usable in Kenya.

Good design is essential where passive cooling methods are considered as part of an overall energy efficient building. Environmental design should follow three fundamental steps; prevention of heat gains (protection), modulation of heat gains (modification) and heat dissipation. Protection includes, careful landscaping, planning and design of building layout, interior furnishings and external construction materials, together with solar shading, thermal insulation and a careful control of heat gains. The modification of heat gains, depends upon the heat storage capacity of the building, which if carefully considered and well designed can improve the overall thermal comfort of occupants by removing excessive temperature swings. Heat dissipation deals with the natural removal of internal generated heat, from people and processes within the building, usually via radiative, evaporative, convective or ground cooling.

This review concentrates on these passive cooling methods and designs, and discusses a number of different solutions for modern office buildings, examples consider hot dry climates and temperate areas.

2.0 Prevention of Heat Gains (Protection)

A fundamental element is the overall design of the building, its location, landscaping, site planning and building morphology. Of particular interest is a complete understanding of solar radiation, solar shading, thermal insulation, surface properties (texture etc) as well as control of internal heat gains from appliances, metabolic heat and artificial lighting is also crucial. Such vital decisions play a key role in determining whether the building will eventually provide the given level of comfort and energy conservation.

2.1 Location, Landscaping, Site Planning and Building Morphology.

Landscaping and bio climatic planning can aid the provision of passive cooling. Although the use of shelter belts in temperate regions is usually to prohibit wind and its adverse effects, in hot climates the use of shelter belts around a building can produce localised areas of cold air, which can then be drawn into the building, providing a source of cooler air. Alternatively they can also be used to alter the prevailing wind direction for one more favourable to cooling the building. Santamouris and Asimakopolous (1996, #10478) suggests that such landscaping can help provide solar protection of both buildings and pedestrians, reduce outdoor air temperature, aid wind enhancement and improve humidity levels. The use of ponds, pools and water falls, etc., can also have a beneficial effect on the microclimate of an area by reducing the ambient air temperature either through evaporation (latent heat) or with the hot air coming into contact with the water surface which is cooler. However, improper design and maintenance can lead to high humidity, stagnation or algae problems.

Santamouris and Asimakopolous (1996, #10478) define the most desirable shape of a building as "one that loses least heat during winter and accepts the least amount of radiation during summer". In their estimation, that volume is approximately related to thermal capacity, while exposed surface area is related to the rate at which the building gains or loses heat. Therefore, the ratio of volume to exposed surface area can be used as an indicator of the speed at which a building will heat up during the day and cool down at night. A high volume to surface ratio is desirable for a building to heat up slowly, since the small exposed surface helps to control heat losses and gains. In hot climates the area exposed to solar radiation is more important than the total exposed surface. During summer in low latitudes the roof is the surface most exposed to solar radiation followed by the east and west walls.

Santamouris and Asimakopolous (1996, #10478) discuss an alternative approach in which the ratio of the surface in solar exposure is divided by the overall surface area. The ratio of summer to winter values reflect the amount of seasonal solar shading inherent in the building. Typical examples for different climates are given such as in hot dry climates, the building should maximise south and west walls (to reduce heat gain), minimise surface area, (to reduce heat gain and loss), maximise building depth (to increase thermal capacity) and minimise window wall (to control ventilation heat gain and light). Similar requirements are given for warm humid, composite, Mediterranean, cool temperate and equatorial uplands climates. Volume to surface ratios do not however account for the thermal characteristics of the building fabric or the effects of solar gain, which can also determine the building's thermal performance. Designing into the building a number of energy saving measures, such as extra insulation, a trade off between such measures and the restriction of optimum shape might be possible. Although in practice, externalities such as planning regulations, site conditions, architectural styles, etc., are important determinants in the final design of a building. The authors place importance on architectural elements such as shading devices, courtyards etc., and on designs that encourage wind channelling into the building and permit ventilation throughout the occupied space. Where the internal design of such passively cooled buildings encourages the passage of air through the space, partitioning should create a larger space of the windward side, and in larger building cross ventilation is preferred. High ceilings allow thermal stratification, decreasing the transfer of heat through the ceiling. In buildings with very high ceilings, stratification allows the occupants to inhabit a cooler region.

The orientation of a building should maximise winter exposure and allow easy manipulation in summer. However building orientation is usually governed by the position of roads etc, with the main facade facing towards the road. In such buildings the south side can usually be shaded during summer and is the best side for solar heat collection during winter. Buildings on east-west roads are ideal for both summer cooling and winter heating needs. Examples of ways to improve the thermal performance of buildings on a south-north road, such as orientating the short facade to the main street are given by the authors.

The effect of orientation on the thermal load of a Egyptian office building is examined by Aziz and Hanna (1991, #6318). The authors studied the impact of rotating the building through 45°, 90° and 135° east of a southern reference point. Results indicate that a 90° rotation decreased the total annual loads of the whole building by 10%. The authors also examined optimising existing conditions. For example, external shading was increased from 0.6 to 0.9m, by extending the overhang of the west facade windows. Other changes included additional insulation to the external envelope, reducing infiltration from windows by upgrading the frames and painting the external walls a light cream colour. Conclusions drawn following the thermal analysis suggest that the most effective measures to improve the energy efficiency of the office building, was the addition of roof insulation and optimizing the external shading of windows, thus achieving a total saving of 36.5%. The authors noted that proper and thoughtful design could have achieved the same savings from the beginning.

The colour of the external surfaces is important in determining the heat absorption of the building. Generally the solar absorption decreases and the reflectivity increases with lightness in colour. The more solar radiation a surface absorbs the hotter it becomes, while the more it reflects, the colder it stays. Santamouris and Asimakopolous (1996, #10478) noted that temperature differences of up to 27°C had been reported between two surfaces on the same east facade, one with an absorptivity of 0.9 and one with 0.2 in a 52° N latitude. Orientation effects can be reduced with light colours, with differences of up to 23°C being reported between different orientations for grey painted walls compared to only 3.0°C for white washed walls. Ceramic materials such as cement, gypsum and lime are highly reflective and suitable for hot climates. The authors noted that, by changing the colours in hot sunny climates with dark colours could reduce a cities air temperature by as much as 2.8°C. The colour of the building exterior can also affect the glare and light in the streets, and by changing the uniformity of the facade by introducing overhangs etc., can help pedestrians.

2.2 Shading and Other Solar Control Techniques.

2.2.1 Pre-Design Tools.

Several design tools have been developed to provide guidance with potential shading problems relating to site and building type.

Yezioro and Shaviv (1994, #8668), present a method by which the mutual shading between buildings can be quantitatively and qualitatively obtained, by the calculation of a geometrical shading coefficient. Such a tool allows an architect to plan open spaces as well as determine the location of passive solar collectors. It enables a quantitative evaluation of hourly, monthly or seasonal exposure of any given surface to the sun to be obtained, then this data can then be included into a dynamic simulation model, ENERGY for the determination of thermal performance of buildings. The qualitative evaluation is undertaken using a commercially available software, that allows three dimensional representation of data. A ray tracing algorithm is applied, as a function of date and hour. The authors state that the model has been evaluated by comparing numerical results of a test case with actual shading information, leading to a good agreement between the two. The comparison also highlighted the tools ability to analyze the mutual shading between complex buildings and elements as well as its ease of use.

The quality of the solar protection of a building is the focus of Millet's (1988, #3225) work, in which he uses a solar heat gain coefficient "Us", calculated by adding together the heat gains for each of the surface components. The thermal comfort is thus derived based on the assumption that a lower Us coefficient provides greater levels of comfort. Although the combination of other factors, such as thermal inertia, orientation and ventilation also plays an important role in the overall determination of comfort. By comparing the coefficient based on these other factors with that linked to the coefficient based on solar gains, the relative importance of solar gain factors can be determined. The derived coefficient is defined as an average heat gain due to insolation over a given period, expressed as a ratio of the volume of the building. The ratio represents the building in a specific solar radiation environment, and depends upon the reference period chosen. The derived coefficient should to be compared with site specific information, for example, in warm tropical climates, comfort conditions would be achieved if the temperatures in the building remained lower than the maximum outside temperatures. Inside temperatures would be further improved if the building was east facing, since solar heat gains occur when the outside temperatures are not too high, and the building is well ventilated and enables the internal heat gains to be evacuated. The authors' have compared their model with real experimental data and results have shown the model to provide good agreement.

The use of a nomograms is outlined in two studies, Jorge et al (1992, #6687) describes their use in Mediterranean climates as a tool to optimise the use of external fixed shading devices.They were developed in response to the over complicated and non user friendliness of existing toolswhich, did not provide accurate analytical information to properly assess the performance of a shading devices, as is the case, with basing analysis of sterographic projections. The authors explain how the shading nomogram was developed and how it is used. The efficiency of shading devices is defined as the fraction of the total incident radiation transmitted through the opening. This time dependent coefficient is a geometric variable depending upon the shading device opening system geometry, sun position wall orientation etc. Jorge states that existing research has shown external shading devices are more effective than internal ones, but their efficiency depends on their orientation. Adequate shading for east and west orientations can be provided by an egg crate shading device, especially if the vertical components are at an angle of 45° towards the south. Also, for south east and south west orientations, while a frame shaped shading is most effective, horizontal shading is also found to be effective.He concludes by stating that the presented nomogram can be used as a practical design tool to evaluate the energy efficiency of a fixed external overhang, or to design its adequate dimensions, if the daylighting is not an important design requirement. It can be used to assess the performance of a shading device in the region from 35° to 50° latitude, with a maximum error of 10%. It allows determination of the appropriate set of sizing combinations to estimate the energy requirements for designing a new overhang or qualifying an existing one in terms of energy. The overhang shading device is an appropriate typology of solar control for a south facade and not recommended for east-west facades.

Nomograms are also used by Calderaro (1990, #10886) to determine passive solar and cooling calculations. Although the paper focuses on passive solar design solutions, some work has been undertaken on passive cooling systems and several simulations have been carried out for different system configurations through ratio related to different reference conditions for the occupants

2.2.2 Shading - Devices

Several authors discuss solar control techniques in detail, including Yannas (1990, #10846) categorises them into three main types. Geometry and aperture regulation, enabling orientation, tilt and opening size to be altered. Sunbeam construction: shading; these devices are governed by the site, building form and aperture components, and finally solar optical properties, include details of the glass and building surfaces.

The use of external shading devices to alter natural ventilation and daylighting is outlined by Tsangrassoulis et al (1997, #10571). Twenty eight configurations of shading device were experimentally tested in the PASSYS test cell to evaluate airflow and daylight transfer through the solar control devices. The study considered both vertical and horizontal louvers, made of metallic sheets with a matt white finish and experiments were performed under various tilt angles. A single tracer gas decay method was used to measure ventilation rates within the cell. The author outlines how the daylight coefficients and corresponding data were established and by using empirical and Computational Fluid Dynamics (CFD), how the air flow through the large building can be achieved. In conclusion, the report gives a variety of correction coefficients for openings equipped with vertical and horizontal shading devices set at various tilt angles. The obtained coefficients were then used to recalculate the experimental data, and this corresponded well with actual measured results.

A market study of solar shading devices in the EU has been undertaken by Alcock et al (1998, #11150) in which shading devices for cooling as well as for lighting purposes are considered. Briefly outlined are the different types of shading device commonly used in buildings, including exterior, interior, movable systems (louvers, awnings etc), fixed systems (overhangs) and glazing treatments. The report also considers the potential for the introduction of shading devices in retrofitted buildings. The sheer number of supplies, products, costs, etc have meant that no such details have been included in this report, although a good overview of current shading devices is well presented.

Stevens and Willis (1995, #8797), Andre et al (1993, #7292) and Kroner (1987, #6692) all discuss case study buildings in which solar control measures have been employed to improve the internal thermal comfort for occupants. The UK's Building Research Establishment's second generation low energy office building is described by Stevens and Willis (1995, #8797). It has three storeys, with total floor area of approximately 2000m^2, taken up by cellular perimeter and open plan offices. The building makes extensive use of glazing on both north and south elevations, with external shading. The building is naturally ventilated via openable windows and trickle vents. Future reports will undoubtedly reveal how successful the design has been in achieving its aims.

Andre et al (1993, #7292) outline in some detail a building located on the outskirts of Arlon, Belgium, which was built to a passive solar design and forms part of an IEA Solar Heating and Cooling project. Investigations undertaken during the original project highlighted several comfort problems, especially in the direct gains zones. This paper reports on a second, more refined thermal comfort study. Although outlined only briefly here, the authors go into some detail about the building and its components. Being rectangular, elongated from west to east the building comprises of two stories, with a trapezoidal cross section, having a maximum height of 10.75m (south facade) continually decreasing to 4m on the north facade. It includes not only office and meeting rooms, but also amphitheaters, which are separated from the glazed south facade by concrete walls and narrow sunspace areas. The first study revealed that overheating was a major problem, especially in summer in the offices on the first floor. The second investigation found that the devices in place to combat overheating were insufficient, and that such overheating can be a major problem even in temperate regions such as Belgium, and with overhangs or sidefins it is difficult to control the rise in temperature. Further the placement of windows, shading walls and beams, should be carefully analysed for extreme conditions (sun high in the sky) prior to final design selection. The authors noted that, in such buildings, mechanical ventilation appears to be necessary since results indicate that ventilation is the only mechanism that has some impact on thermal comfort, with altering other environmental variables such as daylighting.

A conclusion also reiterated by Maldonado and Bragas (1990, #10883) who note that while passive cooled buildings aim to achieve a level of thermal comfort they emphasize the need for adequate provision of additional heating and cooling in many buildings. They state that nowhere in the warmer southern Mediterranean zones is the outdoor temperature close to the comfort zone (18-22°C) during the coldest parts of winter. Equally, in the majority of areas in continental Europe the warmest outdoor air temperatures never reach comfort zone temperatures (24-26°C). Therefore as the desire to incorporate passively integrated designs into modern buildings in different climatic regions grows, architects and designers must be aware of the limitations and be prepared to provide backup systems when environmental parameters stray outside the boundaries achieved by passive systems. Simulation can play a key role in this decision process.

Kroner (1987, #6692) discusses a study initiated in the late 1970's, in which nineteen, passive solar commercial buildings were designed to determine their potential for passive solar technologies for heating, cooling and lighting. With regard to daylighting the following were investigated; windows to reduce artificial daylighting needs, lightshelves, clerestories, roof monitors, and sunspace borrowed light and skylights. Three levels of thermal mass were investigated, high mass, localised mass (Trombe wall, where the location of mass is designed to provide heating and cooling for a specified area), and low mass. The use of high mass, it was found, does not necessarily combat any thermal comfort problems, because it can contribute to acoustical problems and can create difficulty in integrating mechanical systems. For natural ventilation, conflicts sometimes arose between shading devices and apertures impeded ventilation flows. Manually operated ventilation control strategies appeared to be more effective when they are simple, close and familiar. The study found the passive solar building could be operated in a wide range of climates from cold to warm. In conclusion the authors found that passive solar strategies are appropriate design strategies for commercial buildings, leading to significant energy savings from little extra capital cost as well as occupant satisfactions above average.

Pitts and Georgiadis (1994, #7993) outline a similar case showing the results of a laboratory study of the pressure difference flow relationship for air movement through windows when a venetian blind is also in place, for a modern office building. The study conducted in a wind tunnel, examined several window and blind configurations, including no blinds, 0° blind angle, 45° and 85° angles. The authors concluded that thin cross section shading devices, such as venetian blinds may be used up to fin angles of about 45° without any significant reduction in ventilation air flows. In fact some evidence suggests that the use of suitable angled blinds may actually enhance air flow through partially opened windows. This aspect is under further investigation by the authors. They do however note that, if shading devices with angled fins are to be used in conjunction with natural ventilation flow openings, care should be taken to ensure that the angle, width of fin and sun altitude are carefully considered to optimise any benefits. Other similar studies include Brandle and Boehm (1982, #1336) and Palmer et al (1994, #8387) who describe the operation and simulation of these devices, primarily as passive solar devices, although they are used to help cooling in the summer. Both studies report on the energy saving potential of these devices when used in combination with other measures.

2.2.3 Shading - Devices - Automatic Controls

Dounis et al (1992, #11157), (1995, #11151) and (1996,#10959)investigates the use of automatic control devices for shading and thermal comfort. The study examines a building of high thermal inertia, with large south facing windows, outside shading and mechanical ventilation. The building is equipped with an adaptive control strategy utilizing an intelligent controller, although providing only suboptimal control, it can easily be implemented and modified for application in different buildings. The controller adjusts the environmental conditions within the acceptable region and can change its priorities according to the type of demand from the comfort zone. The control strategy also attempts to achieve maximum energy savings by reducing the operation of the auxiliary heater and cooler and exploiting the capabilities of a passive solar building design. The intelligent controller decides, using an ON/OFF operation, to change the level of thermal comfort in real time, for example, the controller attempts to regulate PMV (predicted mean vote) within ±0.5 deviation zone, ventilation is achieved by natural means, as well as using fans. The author describes the control system in more detail in the paper. In a follow up paper Dounis et al (1995, #11151) extends the above study and investigates a new approach to optimal control, utilising an expert system with an embedded knowledge. The system aims to make the correct decisions about which actuator to use, based on environmental measurements made in real time. The new system employs fuzzy logic as opposed to the mathematical representation of PMV, and as such is capable of handling complicated arrangements such as multispace buildings and variable user requirements, by extending the rule base. The chosen system does not operate as "optimal" but "satisfactorily" provided the correct rules are chosen properly. This process is outlined by the authors, who stress that there is no single meaningful set of rules. The aim is to determine one that keeps the environmental conditions within the comfort zone and minimizes the usage of auxiliary energy at the same time. By means of an example the authors simulate two extreme climatic conditions, for both January and June which are both described in the paper. In conclusion the authors state thatthe user provides the information on the comfort on the living or working place, by introducing their activity, typical clothing ensemble and the desired thermal comfort level. The system controls auxiliary heating and cooling, the ventilation window, the shading device and artificial lighting. They also state the cost of such a system is low, and its components are currently commercially available, and the control of thermal comfort leads to indirect control of the indoor temperature and the relative humidity. The width of the oscillation is low and does not generate thermal discomfort.

The feasibility and performance of passive climate control systems are discussed by Lute and Paassen (1993, #8548), (1993, #8549) Liem and Paassen (1997, #10554). The outlined system uses a control system to predict the future thermal behaviour of the building and uses this prediction to maximize the outdoor contribution to the indoor comfort and minimise the energy consumption. By allowing a building to slightly deviate from the temperature setpoint, the control system attempts to maintain the indoor temperature between the upper and lower temperature boundaries, determined by thermal comfort theory, minimising energy consumption as a consequence. The control system predicts indoor temperature in advance in order to determine the required control actions. The optimal predictive control system is derived from an estimated linear ARMAX model of the indoor temperature behaviour, including controlled inputs (radiator, window etc) and uncontrolled disturbances, (internal heat and outdoor climate). The system correspondingly generates a series of control actions, derived from temperature offsets, energy consumption and limitations of heating systems etc. The mathematical derivations of these control actions are outlined by the authors in the paper. The authors outline a simulation exercise in which their system has been tested, for typical winter and summer situations. In both seasons the control system reacts and implements actions that bring the environmental conditions within the building back into a thermal comfort state. In conclusion the authors state that such a system could be adopted to other types of buildings with other components, but in this case, the simulations showed that the control system performed as expected.

3.0 Modulation of Heat Gains (Modification)

The modification of heat gains, depends upon the heat storage capacity of the building, which if carefully considered and designed for can improve the overal thermal comfort of occupants, by removing excessive temperature swings.

3.1 Thermal Storage

A series of guidelines for estimating the cooling potential of a buildings thermal mass is considered by Paparsenos (1990, #10889) He examines the number of different ways used to determine the thermal mass of a structure, for example total dynamic performance methods, however because of the strong interrelationship between elements it is difficult to separately study each element individually. Phenomena such as surface convection, internal and external longwave radiation exchange, solar radiation absorbence, etc., all have their own effect on the dynamic performance of a building element with thermal mass. This is why the response function and numerical method described by the author tend to be geared towards the total dynamic performance of a building. Paparsenos then discusses the indices and simplified design methods used by a number of other authors, but notes that while these methods recognise the significance of thermal mass on cooling (or heating) load, they can not be used for the calculation of optimum thermal mass level and distribution. Principally because as thermal mass is added to the space, the cooling (or heating) load will decrease to an asymptotic minimum value or will decrease in a discrete manner to a minimum value. The author concludes by admitting that where a building requires both heating and cooling at different times of the year, any determination of optimum thermal mass level and distribution will be difficult. This is further complicated by the lack of appropriate guidelines Simulation is an integral design tool in such situations, provided the algorithm has been modified to deal with the various passive cooling techniques. Any simplified design guidelines will only become widespread, if they are accompanied by a simplified design method and if information concerning physical and optical properties of mass produced or locally produced thermal mass materials, become easily available to the designer.

The advantages and disadvantages of using thermal capacity to reduce mean temperature and temperature fluctuations in massively constructed offices is discussed by Evans (1992, #6770). Thermal mass typically occurs in the form of floor/ceiling slabs and walls and partitions. By exposing slabs, heat can be absorbed and a reduction in air and radiant temperature achieved. Night time and fresh air ventilation can increase the daytime capacity. Even with no mass, exposed night ventilation through open windows may also be beneficial. With suspended ceilings and raised floors cool night air can be mechanically driven through these voids to cool the slabs, ventilation air delivered through the voids during the day is then cooled by these slabs. Evans does however note that unless the building is designed and managed to minimise heat gains, the use of thermal mass and night time ventilation could provide disappointing results. The author includes six case studies outlining the principle construction details and how thermal capacity has been used in each.

Givoni (1994, #8663), monitored three buildings with the same heat loss coefficient but with different mass levels. Measurements were conducted for shaded and unshaded windows configurations in order to investigate the effectiveness of mass and night ventilation in improving the daytime temperature and comfort conditions. The baseline condition was the unventilated state, as in all buildings, average indoor conditions were higher than outdoor maxima (medium mass building rising 6.7 °C and high mass 4.5 °C). Results indicated that night ventilation coupled with low building mass had little effect on reducing the indoor maxima. Although in high mass buildings, night ventilation was very effective in lowering the indoor maximum temperatures below the outdoor maxima, especially during the heat wave periods. For example, on a very hot day, with outdoor temperatures of 38.7°C, the corresponding indoor temperature was 24.5°C, within the comfort zone. With windows open all day and night and fans activated during the night, maximum temperatures of the high mass building were lower than the outdoor maximum, while that of the low mass building was close to that of the outdoor. In conclusion the study found that a reasonably insulated high mass building ventilated at night, with shaded windows, but with dark colour on its envelope could possibly maintain internal temperatures 14°C below the outdoor maximum, compared with the low mass buildings which did not perform as well. The results cause the author to question the commonly held belief that in hot humid climates low mass buildings are more appropriate.

Alexander and Jones (1989, #4173), used a dynamic thermal building model to investigate the use of alternative methods of providing acceptable summertime office conditions within UK commercial buildings, other than air conditioning. The paper looks at the use of controllable ventilation, the use of external solar shading devices, the use of high internal thermal mass, and the use of night time ventilation to flush out stored heat gains. Simulations were carried out for summer in a hypothetical building located on an unobstructed site near London. Light and heavy weight variations of the building were considered, with the amount of external glazing fixed for all simulations, (based on 50% of the external elevation for all orientations (except from the blank north elevation)). Where external shading was applied, the equivalent of a projecting horizontal awning of 2.5m depth was assumed on all facades. A minimum ventilation rate of 1.5ach during occupancy was chosen, with overnight infiltration set at 0.25ach. Ventilation was increased to 6 and 12ach for night time purging. External shading devices were found to be effective in both reducing cooling loads and radiant temperature levels, thereby increasing comfort. Through the combination of responsive day time ventilation, night time purging, solar shading and thermal mass a significant reduction in cooling requirement can be achieved. The authors found that at moderate levels of internal gains (approximately 40 W/m^2) reasonable environments were predicted, without active cooling. At higher gains (<60W/m^2) active cooling could be avoided, although some lowering of the expectation level of comfort may be required. The authors noted that even with air conditioning test cases, some comfort criteria were not always met, mainly due to radiant gains increasing the radiant temperature.

Meierhans (#8639, 1993) discusses a hydronic slab cooling system installed in a Swiss office building, sited in a rural area on a slope of Lake Zurich. Average temperatures are between -15°C and 0°C for 1400 winter hours. Internal radiant loads can reach high levels, causing some discomfort to occupants. Simulations were conducted on the office building and results indicated that for at least five months some cooling is necessary. Night cooling for security reasons is limited, therefore alternative strategies were examined. The designers' chose a phase shifting slab cooling system. Heat flows through the thermal mass occurs in only one direction, contrary to traditional systems with a surface approach in which the heat flow is driven by fluctuating air temperatures, leaves and enters alternately. In the building the heat is stored in the concrete mass of the structure during the day, and the structure is cooled by a hydronic system, the heat being discharged by air/water heat exchangers during the cool night hours. Only the minimum outside air volume required for hygienic reasons, is supplied to the occupied zone. To avoid the need for flow control equipment and individual temperature control in rooms, a supply inlet was modified to enable the supply air to be re-heated dependent on the load. The supply air has a constant cold deck temperature of approximately 19°C. Before it enters a room, the air is warmed up to within 1 to 2K below the room air temperature by passing through the pipe system of the lamp mountings. This system therefore enables the outdoor air to be cooled enough to reach the required supply air temperature, and the resulting dehumidification is limited to only a few hours per year. At the same time, condensation of humid air on the coldest parts of the cooling system is prevented. The author has developed a dynamic simulation model of the ceiling based on the finite difference method and in this respect the author briefly describes the mode and tests a variety of different parameters on the indoor climate.

A similar design technique called Termodeck is discussed by a variety of authors including Husslage (1994, #8389), Winwood (1996, #10909) Cook (1996, #11161), Bunn (1995,#11160) and Winwood et al (1997, #10951). The Termodeck system is an air cooled slab component system, manufactured from concrete with voids running through the unit, carrying cool air. The air flow through the hollow core helps to reduce excessive temperatures during the day, in the warming season, trapped heat within the system helps to offset heat loss outside of office hours. Husslage (1994, #8389), outlines a number of advantages with this system over mechanical ventilation in heavyweight buildings, including the large surface area of the hollow core which allows a more efficient cooling of the thermal mass deeper into the building. The system permits shorter, and therefore cheaper, air ducts because the supply channel and the slabs are close together. The air entering the room from the slabs is the same as the Termodeck itself. Therefore, during office hours cold fresh air can be supplied to the slabs without recirculation or heat recovery, which is usually necessary to avoid cold draughts. The author suggests that the Termodeck principle can satisfy high fresh air demands, such as $5m^3/m^2.h$ without recirculation of polluted air. Husslage also outlines two Dutch case studies where the system has been used successfully. Examples of Termodeck installations are discussed by Winwood (1996, #10909) (1997, #10951), Cook (1996, #11161), Bunn (1995, #11160) and (1994, #10908), Isfalt (1996, #10264) and Adamson (1991, #9939)

Beggs et al (1995, #9431) discusses the use of fabric thermal storage to reduce or eliminate the use of air conditioning in UK offices, by using a system similar to Termodeck. The proposed system involves the addition of a screed surface on the top of the existing solid concrete floors, under which is placed a series of igloo like nodes interconnected by semicircular tubes in contact with the concrete floor. The nodes and connect tubes are made from perforated metal and once in place are covered by a 75mm thick cement screed, to form a hollow core screed. External air is drawn in during the night through the hollow cores at low velocity, thereby cooling the floor and slab. This stored "coolth" is then used to cool down the warmer outdoor air entering the building, or alternatively to temper rising internal temperatures, by cooling down the internal air. This system can present a larger surface area to the outside, than floor void systems, resulting in higher heat transfer rates. One of the problems with floor void systems, is the need to keep air velocities low enough to cool a significant quantity of the supply air, while still creating the degree of turbulence required to achieve good heat transfer. The author notes that with the hollow screed system it should be possible to achieve a high degree of turbulent flow at relatively low air velocities, helping to minimise fan power consumption. Other benefits include, elimination of raised floors, reduced load placed on existing floors because the proposed surface represents only 53% solid compared with conventional screed surface. The authors have modelled the potential performance of such a screed system, with results indicating that the system should behave in a similar manner to hollow cored slab systems, although the more even distribution of the hollow screed system should prevent the formation of cold spots. The nature of the heat transfer will vary with the material in contact with the hollow tubes, and therefore behave in a different way than the monolithic systems, because the screed will have different heat transfer properties than the solid concrete floor. The authors state that while the screed is being cooled by forced convection, it will receive heat by conduction from the concrete floor. The nature of the heat transfer mechanisms acting during night time charging, are not as significant as during the period when charging has stopped, and before the discharge cycle begins. During this down period, heat will be conducted into the screed, increasing its temperature to that approaching the temperature of the concrete floor slab. As the discharge cycle begins, both the screed and concrete floor slab should be approximately the same temperature. The author has used a finite difference approach to model the complex heat transfers and further details are contained within the paper.

Holmes and Wilson (1996, #9533) outline a numerical simulation in which they suggest that suspended ceiling and floor voids could be used to introduce cool air into a building at little extra cost. In both cases mechanically driven cold air is pushed through these voids to pre cool the building. This means that only minimal cooling will be needed provided that sufficient free cold air can be found to drive the system. The authors discuss how such systems can be modelled, the ability to provide comfort during typical summer conditions in the UK and the potential for reductions in energy consumption when compared to a conventional Variable Air Volume (VAV) system. Particular attention should be paid to ensuring the system provides comfort, and not adversely affects the health of occupants. A further note is that ventilated slab systems are prone to more temperature stratification than natural ventilation. The authors outline the basic requirements of the system in terms of heat transfer, and consider heat flows within the cavity as well as the effect of the number of transverse elements upon performance and frequency response of the system. Using their own calculation method (algorithm called ROOM) the authors attempt to calculate the performance of a typical ventilated floor system, comparing it to a typical natural ventilation system. Predictions show that the memory of the slab is approximately 1 month, making a proper representation of the system performance unlikely with cyclic weather data. Although predicted internal conditions for a single day cycled to steady conditions with the same day in its proper place within the month, could be useful. Results indicate that ventilation of the slab will reduce space temperature and a high convection coefficient could be an advantage. The authors undertook some basic comparison between the energy required to drive a typical VAV system, only operational when occupants are present, and a passive slab system which requires a fan working all night. However, a more detailed investigation would be required to draw any significant results from this part of the paper.

3.3 Night Cooling.

The intentional introduction of cool night air into a building immediately acts to improve the thermal comfort for any occupants (night workers, residential occupants etc.). Although more significantly it acts to reduce the peak temperature of the following day, by cooling the thermal mass of the structure and releasing the stored, so called "coolth" during the next day. To be most effective the night cooling air flow paths are commonly different from those of day time ventilation air, being aimed at cooling the structure rather than providing occupant comfort. Therefore air introduced during the night may pass through the building components themselves, or through specially designed voids in walls rather than through the actual occupied space. The thermal mass of the structure, therefore, plays a vital role, but a thickness of more than 50mm has little effect on the diurnal temperature fluctuations, but does play a more important role in weekly or seasonal variations.

Other important considerations include spatial layout and the use of partitioning etc. (Kolokotroni, 1995 Annex 28 low energy cooling technologies), as well as external weather conditions. According to Kolokotroni night cooling is best suited to hot or moderate climates with large diurnal temperatures over the summer. For mechanical systems, night temperatures must be cool enough to make up for 1°C to 2°C heat gain due to the fans, and the humidity ratio of the air should be less that 15g/Kg dry air, because the technology provides mainly sensible cooling. In simulation exercises night cooling, depending upon the external heat gains and thermal mass, is capable of providing cooling for up to 40 W/m^2 of internal heat gains. It can lower the daytime temperature in heavyweight structures by about 3°C. However, in humid climates, it is important that night cooling does not introduce excessive amounts of moisture at night, to avoid causing discomfort the next day.

Ventilating at night allows sensible cooling of the internal space and furniture etc, as opposed to cooling the thermal mass directly, and can be the cause of moisture problems, these are considered by Phillip et al (1986, #3002). Cool night air typically has high relative humidity, this excess moisture can be absorbed by the building and its furnishings, although the process releases a large amount of thermal energy, which can counteract the sensible cooling benefits provided by free night cooling. When the air conditioning system is restarted any excess moisture is condensed, and any absorbed moisture is desorbed and removed by the system, thereby providing local cooling. However, the removal of absorbed moisture, represents a latent heat load during starting and restarting. The authors note that little data exists on the values of these processes, and therefore the aim of the current study is to attempt to provide moisture response data for a variety of materials, thereby providing useful data for design algorithms that calculate sensible and latent loads. Typical exposed materials were chosen such as, reinforced concrete, painted Gypsum Board, Cotton cushion, newspaper, Letters etc., and then tested in an experimental chamber set up to simulate the daily cycles of high humidity followed by low humidity conditions. Strain gauges were attached to hanging test materials as they cycled through typical high and low humidity ranges, changes in the weight of each sample was recorded. The relative humidity was then calculated The average air velocity adjacent to the samples was approximately 68 ft/min(0.345 m/s). It was found that moisture loss from materials during the low temperature portion of the daily cycle represents a significant latent heat load on the air conditioning system. Materials with a low moisture load, vinyl floor tile and cotton drapery, absorb and desorb relatively little moisture compared to other test materials. With such materials moisture either does not penetrate the surface, or the material has little moisture storage capacity. However, these materials could represent a significant latent heat load, since they are present over a large exposed area. Wooden materials, masonry blocks, concrete, gypsum board wool and cotton cushions all responded to changes in moisture, and were classified as moderate moisture load materials. Concrete and wood, absorb and desorb moisture rapidly at the surface, but the rate of moisture movement into or out of the interior is controlled by diffusion, whilst cotton, wool and acoustical tiles are quick to respond to changes in humidity and have a significant storage capacity. Both types of materials in this group represent a substantial latent heat load at the start of the daily cycle. The final group are high moisture load materials, newspapers and letters for example, which both absorb and desorb significantly higher amounts of moisture than other materials, and as a result represent a very high latent heat load at the start of the daily cycle. In conclusion the authors note that the although the study was limited to fifteen typical materials used in commercial construction and furnishing, they were successful in identifying the existence of latent heat loads caused by the absorption and desorption of moisture in a variety of materials. The major portion of moisture loss from many materials occurs during the first two to three hours of the daily cycle and represent a huge latent heat load, based load per unit time. The result of which would be the system design requiring a large capacity for moisture removal for a short time period and decreased capacity for the remainder of the cycle, or the alternative use of materials or non absorbing paints etc.

NiteCool is an office night ventilation pre-design tool outlined by Kolokotroni et al (1997,

#10570) and developed under the Energy Related Environmental Issues in Buildings (EnREI)DOE programme It is designed specifically for the assessment of a range of night ventilation strategies for UK office buildings and climate, allowing good comparison to be drawn with energy consumption and comfort benchmarks and enabling internal heat gains, ventilation rates, occupancy patterns and external temperatures to be varied. The model is a single zone ventilation model, based on a 10m wide by 6m deep by 3m height, positioned in the centre of a row of offices in the middle floor of three. It includes light, medium and heavy weight thermal mass variations, and external windows are assumed to be clear float double glazing, with internal plasterboard partitions and carpet. Information regarding the building can be obtained from a menu on screen, and contains information about the building, weather, day ventilation, night ventilation and control strategies. User input data includes, internal gains, infiltration airflow, orientation, glazing ratio, building weight, occupancy period, solar protection and shading coefficient and site location for solar positioning. Kolokotroni concludes that the model has been developed to reduce user input and maximise simulation time, with the various systems and combinations available beingexamined in more detail in the paper.

Roulet et al (1996, #9691, #9692) Flourentzou et al (1996, #9841) Van der Maas et al (1994, #8392) and Van der Maas and Roulet (1993, #7067) outline the development of the LESOCOOL computer code, designed to predict the cooling potential of building for night time ventilation and case studies used for validation. The code was developed only to require a small amount of input data, it is based both on the Bernoulli equation and basic solutions of the equation of heat. LESOCOOL is a simplified multizonal model combining a ventilation, thermal storage and heat transfer models, each component being briefly described in more detail in the paper. Required input data is deliberately minimised and includes effective area of walls, floor, ceiling average thermal effusivity; structure initial temperature; power of internal and solar gains and external temperature. The model is PC based with two interfaces, for architects and engineers with little experience of building physics and one addressed to experts. LESCOOL can calculate the cooling potential, temperature evolution and air flow rate in an enclosure ventilated naturally or mechanically. The user can account for convective or radiative heat gains or losses through a closed window, door or very thin wall of a given U value in contact with external air. The enclosure can be single or multi zoned, provided the air flow paths are known and simple, and the model can calculate the temperature response of a single zone submitted to a heat pulse. The neutral pressure level in a large enclosure ventilated by the stack effect can be calculated as well as the instantaneous air velocities and flow rates in each opening for a given temperature difference. However, the model cannot calculate very long periods, or deal with thin or multi layer wall slabs. For multi zone modelling the air flow must follow a single path, being unable to account for interactions, other than ventilation coupling with neighbouring zones. Results of the model have been favourably compared to full scale measurements, examples highlighted in the paper are night ventilation of a LESO office and Gjovik Mountain Hall. The main limitation of the model is that multi zone modelling is only valid for a single flow path, with no branches, although several openings at the same level can be combined. Comparative experiments have shown reliable results, provided the input data is accurately entered. The thermal model is only really valid for infinitely thick walls; simulations of up to one day can be undertaken in rooms with typical masonry walls.

Van der Maas and Roulet (1993, #7067) validate the model against experimental data of a simple stairwell and library situation in a three storey building. For the library the multizonal model produces more realistic temperature distribution than single zonal models, although the dominating air flow pattern should be known in advance. The model does however tend to over predict temperature stratification, because the influence of radiation between walls is not included in the model. For the stairwell, when the ventilation openings were opened at 18:30 hours, the ventilation rate of $1m^3/s$ (approx. 7ach) was achieved, resulting in a significant decrease in inside air temperature. From the model predictions, the authors recommended that to increase the cooling power the opening area at ground level and wall surface should be increased.

Santamouris et al (1996, #10907) suggests that the complexity of some simulation tools reduces their effectiveness as pre-design or actual design tools. Stressing that there is a need to develop integrated and accurate methods to easily calculate the contribution of night ventilation techniques to the building's cooling load, especially during these stages of the design process. In response to these claims the author presents an algorithm based on the principle of "Balance Point Temperature" which has been validated against extensive and detailed simulations (using the TRNSYS model) and experimental data. As part of the validation process 128 various cases, including a variety of building characteristics, indoor temperatures and air changes rates during the night time period were performed. All simulations were carried out by assuming the buildings' were thermostatically controlled during the daytime and free floating during the night, with night ventilation being instigated only when the outdoor temperature was lower than that indoors. The method is not appropriate on buildings with low thermal mass, or for buildings with less than 5ach, and has not been validated for buildings of very high thermal mass and buildings with 30ach or more. The authors consider that in comparisons with simulations run on TRNSYS, where differences of only between 3 and 15% were sufficiently accurate to be able to predict the contribution of night ventilation passive cooling technique to the cooling loads of a building.

Gage (1997, #10557) describes a series of experiments undertaken as part of the European NatVent project, in which as an aid to night cooling and natural ventilation within deep plan office buildings, the value of roof air intakes and ducting is investigated. The basis of this strategy is to reduce the intake air temperature to below the building air temperature. Two approaches have been examined, pressure differences created by the wind are used to drive wind into the intake duct so that it is cooled down to external air temperature, this will only provide cooling when the external shade air temperature is lower than the internal temperature. The other approach is to provide a cool air on top of or in the intake duct. This offers the option of mixed mode cooling, where daytime ventilation air can be cooled to comfort levels at times of high heat gain. Both options were modelled by the author experimentally in wind tunnels and via CFD programs. A number of important design features were raised, such as a preference for hood type intakes since they appear more efficient, and the intakes must be at least 2m above an adjoining flat roof to place it above boundary turbulence. The research to date has provided encouraging results, and the author believes that intakes can be roof mounted in urban areas. The introduction of large low energy fans into the ducts will supply air when there is no wind and when the external shading and temperatures will not by themselves secure an adequate passive cooling strategy. The author has investigated the option of utilizing a roof garden to provide the necessary conditioning of the external air prior to introducing it into the supply ducting. Air is extracted from under the roof garden, and introduced into the supply duct. The roof garden experiments showed that relative humidity is very high when cooling is at is most apparent, and that heat once gained in the garden is trapped in it dissipating more slowly then expected.

Webb and Concannon (#10262, 1996) and Kolokotroni et al (1996, #9885) outline a joint venture which combines field measurements with thermal and air flow modelling of a typical office to determine the possible level of night cooling available using a range of strategies and ventilator configurations. The building, a refurbished 1950's, four storey office building, with large open plan first and third floor was studied during the summer of 1995. Ventilation was provided by 850mmx600mm bottom hung ventilators positioned around the perimeter of the office. Studied over a four week period, and between 18:00hours and 08:00hours Monday to Friday the ventilators were kept closed on one floor and open on the other. During the weekend, the ventilators were either open or closed. The conditions were then reversed for subsequent weeks and weekends. Daytime temperatures of 30°C were typical throughout the study, and was exceeded on several occasions. The internal dry resultant temperatures at 08:00hours were compared against external air temperatures at sunrise, 05.15 (the coolest time of the day). It is shown that some benefit of night cooling can be achieved with high external air temperatures at dawn, for example, with an external air temperature of 14°C, there was found to be a 3.5°C internal dry resultant temperature difference between vents open and closed, while at a warmer 21°C, there is still a 1°C internal temperature difference. The floor with night cooling also remained cooler throughout the following day than the floor without night cooling. Thermal and airflow modelling was undertaken to establish whether achievable air flow rates for a range of UK weather data and combination of openable areas is possible. An expected from the air flow equation, doubling the openable area doubles the flow rate, although the magnitude of this change is wind pressure dependent. With no wind, the openable area must increase with decreasing stack height. In conclusion the authors found that night ventilation reduces daytime dry resultant temperatures by 4°C at the start of the day, compared with an office without night ventilation, and once occupants have experienced such a ventilation strategy, they like it. Modelling has been able to highlight were controls are needed and how best to implement such strategies.

Using a dynamic building simulation program, Bollinger and Roth (1993, #7026), examine, night cooling by untreated outdoor air, night cooling combined with evaporative cooling (to a minimum humidity of 11 g/kg dry air), and ventilation through a false floor, in a heavy weight construction. Simulations were undertaken using a reference room and the TRNSYS model. For the first scenario with 3 ach, the temperature threshold (28°C) is reached at a specific load of approximately 35 W/m^2, while 6 ach permits a load of 41 W/m^2. The authors note that high air change rates permit only slightly higher loads. Therefore above 40 W/m^2 mechanical cooling ventilation would be necessary. The energy demand during the three summer period could be reduced by 18% with the introduction of night cooling, for example with a specific load of 50 W/m^2. Night cooling can also reduce the required cooling capacity of the HVAC plant. The second simulation includes mechanical ventilation with increased heat transfer and evaporative cooling. For only a small improvement, i.e. the introduction of evaporative cooling by humidificiation, the benefits are large. The simulation exercise allowed the supply air to be humidified to a threshold of 10.3g/kg dry air (both day and night). The combination of evaporative and night cooling reduced the energy demand by up to 20% during the simulated period. The final simulated exercise combined mechanical night cooling through a false floor. The maximum room load is about 35 W/m^2 with an air flow corresponding to 3 ach and 42 W/m^2 with 6 ach. Results showed no significant differences in energy consumption. However, the advantage of this system is that room ventilation and night cooling are separate, and very good reductions in energy consumption can be achieved by using the stack effect of an atrium to drive the system. A disadvantage is the difficulty in closing the false floor against outdoor climate in the winter, to prevent heat loss at low outside temperatures. In conclusion the authors suggested that by using night cooling combined with mechanical cooling reduction in energy demand of between 15 to 20% can be achieved. However, decentralised systems with low pressure losses were required, using conventional systems significant energy savings cannot be achieved. The provision of adequate comfort is hard to achieve without a mechanical system. Night cooling is not seen as a replacement for mechanical cooling by the authors more as a supplement to reduce energy cost and refrigeration capacity. Night cooling should be able to work without mechanical systems, running solely under buoyancy forces, however this requires careful planning and cooperation between the architect and HVAC engineer.

The effectiveness and potential of night ventilation in three Greek office buildings is investigated by Geros et al (1997, #10595). Building one (Meletitiki building) is a heavy weight building, consisting of seven zones, and ventilated at night both mechanically and naturally, with an estimated air flow rate of 25ach. It is also thermostatically controlled by air-to-air heat pumps. The study considered a number of operational schedules, both experimentally and theoretically, and these are outlined in the paper. The second scenario, at the University of Athens, is a room located on the third floor of a six storey building which is built from a light structure, and cooled with an air-to-air heat pump. Night cooling was applied, by opening two windows at the end of the day. Both windows were located on the same side and the same operational schedules were tested on this room as with building one. Finally building three (National Observatory of Athens) is a room located on a one storey building, with no air conditioning, but of heavy structural material. Night ventilation was applied in the same way as in building two. The TRNSYS algorithm was used to simulate the thermal performance of these rooms during the measurement period. Results from both experiments and simulation showed that for building one the application of night ventilation, reduced the following day's peak indoor temperature during free floating conditions up to 2.5°C, whilst under A/C conditions this decrease was closer to 1°C. For Building two, the corresponding reduction of the next days peak was only 0.1 to 0.2°C (for A/C conditions) and 0.1 to 0.3°C for (free floating conditions). The authors conclude that the contribution of night cooling for a specific building has to be calculated as a function of building characteristics, climate conditions, applied air flow rate and assumed operational conditions.

Arnold (#9532, 1996) discusses the use of mixed mode systems for environmental control. Passive cooling techniques can be included into such designs, as long as at some point in a cycle the external temperature is lower than a comfortable indoor temperature. Night time cooling satisfies this requirement, and can be used in conjunction with a buildings thermal mass to reduce the onset of mechanical cooling. For most of the year the building will operate under natural mode, with occupants opening and closing windows as necessary. For night cooling to be most effective large expanses of thermal mass should be exposed, however its usefulness depends upon the amount of exposed surface area, the thermal properties of the material (conductivity, density, specific heat), the frequency of the cycle and the swing in temperature. The quantity of heat (or "coolth") that can be stored in the fabric is restricted by the maximum thermal capacity of the material and the amount that it can conduct through the material in each cycle (usually 24hrs). The designer can to some extent determine the surface area as well as the thermal properties or effectiveness of certain materials, for example, the location of insulation on an external wall. The author uses diurnal heat capacity to estimate the combined effect of the heat storage capacities of the building fabric bounding the space as well as the fixtures and furniture, estimating that fabric thermal storage can displace upto 50% of the peak cooling duty. He states that an optimum thickness for each material exists, for example for concrete it is approximately 100mm, so that increasing its depth/thickness beyond this optimum has a negligible effect on the thermal performance of the room. Additional thermal capacity can be achieved by increasing the surface area coupled to the space, although, excessive amounts of thermal capacity can cause occupant discomfort.

The author further suggests that inadequate control is a reason why some overnight cooling systems have failed. The thermal properties of the space and the response of the building users control the rate of heat discharge, and the amount of heat absorbed by the building mass increases as the temperature difference between the space and surrounding thermal mass increases. The author concludes that when using mechanical systems, it is important to remember that night ventilation is time dependent, with minimum temperatures occurring around dawn, which is at the end of the normal off peak tariff window. The optimum period for overnight cooling may well run into the beginning of the working day, therefore starting the change over earlier may be cheaper, but less energy efficient.

4.0 Heat Dissipation

Heat dissipation deals with the natural removal of internally generated heat, from people and processes within the building, usually via radiative, evaporative, convective or ground cooling. The internal warm air is cooled via one of the above methods, and then returned to the space, having lost some of its heat energy.

4.1 Natural Ventilation and Passive Cooling.

The wide variety of ventilation cooling approaches are outlined by Fleury (1990#,10887). Such options include the use of wind towers, solar chimneys, the location and shape of ventilation openings, windows, and the importance of building shape, layout, and orientation etc. The author provides a comprehensive list of design guidelines to enable the architects to design natural ventilation as a cooling strategy. Fleury suggests that architects should design the building to respond well to winds from any direction, choose the most appropriate ventilation strategy for the climate and building conditions, design for both horizontal and vertical air flow, utilise both the wind induced and stack effect, and concentrate ventilation openings in spaces where cooling is most needed. In all 23 suggested points are enclosed within these guidelines. In conclusion, Fleury suggests a variety of future research areas that need more attention, including, improved design guidelines for sizing and distribution of openings and a determination of the convective heat transfer coefficients at room surfaces for a better understanding of structural cooling.

Baker (#1990, #11159) similarly discusses the fundamental differences between cooling in a warm climate and heating and in a cool climate, and how man adapts buildings to provide thermal comfort for whichever climate he is in. He suggests that in comparison, there are less cooled buildings than the vast number which are heated. While traditional forms of heating are widespread, apart from the prevention of overheating, there are few traditional forms of cooling, suggesting that in most cases the normal temperature regime is below that of comfort, which in terms of the potential for passive cooling solutions is a good thing. The prevention of overheating by minimising gains from solar radiation and internal sources, is a more significant problem than the provision of coolth. However, where the climatic situation and building may demand internal conditions be significantly cooler than ambient, the often high level of internal gains mean that auxiliary cooling is often necessary. Occupant comfort models, indicate that where conditioning is necessary, it is most effective on a local scale, thus localised coolth emitters need to be developed. The author suggests for example, an opening in the external wall which can modulate and direct the prevailing wind onto the occupant. Another proposed system is a cooled floor, providing stratification and stability of the lower layers, providing a good occupied zone. The author concludes with a look at psychological reactions which could also be used positively, without the expense of mechanical chillers. For example, visual clues, such as furnishings, decor, etc., can influence occupants thermal comfort with little active conditioning. Other psychological influences could include the effect of glare. Research suggests glare may be more acceptable in cool climates, than in warm climates, possible due to its association with thermal discomfort. Therefore shading design should consider the brightness and positions of isolated surfaces which can be seen by the occupants, as well as considering the role of shading to prevent direct radiation.

Santamouris et al (1996, #9886) outlines a number of natural ventilation studies carried out within the framework of PASCOOL EC. Full scale and test cell experiments were conducted during a summer period, when single sided and cross ventilation, as well as air flow through large internal openings were also studied. Tracer gas studies were undertaken to derive natural ventilation airflow rates and determine any limitations of their use. This experimental data was then used to validate existing models and develop new ones. Both full scale (in Athens and Spain) and test cells (Athens, Belgium,BBRI and Portugal) were used to measure single sided ventilation. Data from 76 different configurations using the decay tracer gas technique for all but the BBRI test cell, where constant injection was used, were complied. A variety of simplified and network models were used to calculate air flows, all of which gave similar predictions. However, on closer examination revealed that these experiments were all inertia dominated, the wind effects being practically disregarded for the case of single sided ventilation. There was also a disagreement between predicted and measured air flow rates, the correlation coefficient between the two sets of data never exceeding 0.4. Therefore a new model was developed and validated to overcome this disagreement. The CF model multiplies the network model predications by a correction factor, to give a more accurate result. The mathematical basis for this model is outlined in the paper, and has been validated by the authors with success using data from other single sided ventilation experiments. Cross ventilation was also studied using tracer gas techniques in a real apartment as well as in a test facility.

Santamouris et al (1996, #9886) also used the Aynsley model to derive discharge coefficeints for a single zone cross ventilation configuration. The author's experiments found that the hypothesis of homogeneity which is adopted by all existing models was no longer valid. Its absence imposes the necessity of concentration field measurements, which is currently constrained by the existing gas analyzers. The research of larger internal openings focused on whether the discharge coefficient of 0.4 is valid for real buildings. Its value has been previously experimentally derived, and was charecterised by strong stratification and an important boundary layer flow. Another important focus of the research was whether the flow resistance's formed by open doors in series can be predicted by a simple Bernoulli model and usual discharge coefficients. The Optibat test cell in Lyon and the PASSYS test cell in Athens were used for the experiments. The new software tools EXAC1.0 and PASSPORT-AIR were used for the calculation of the theoretical air flow rates. Experiments found that the discharge coefficient varied from the one originally proposed. In conclusion, the authors noted that although still much needs to be done, they have succeeded in developing new research tools, design methods and empirical knowledge suitable to design purposes through the framework of this project.

The use of bioclimatic design, using natural ventilation and passive cooling strategies, in non domestic buildings in Mexico is discussed by Roberto and Chavez (1994, #8659). Such buildings are characterised by large external and internal heat gains, high running costs for air conditioning, electric lighting and thermal and visual discomfort problems. The avoidance of over heating and the provision of cooling represents the two main sides to passive cooling strategies. The potential for passive cooling and natural ventilation design is tested in a library, of total volume 32,000 m^3 and equipped with a mechanical ventilation system. It also has a large south facing glazed facade. The inlet for the ventilation opening is 4.5m^2 located in the main south facing entrance, with its outlet positioned on the roof. Initially, the investigation consisted of monitoring the ambient conditions, interviews with users, solar penetration and shading analysis using scale models, followed by interpretation of results and a proposal of passive cooling alternatives. Results indicated that all areas exceeded comfort criteria of 23°C, except near the north facade. The southern parts represented the higher temperatures of around 30°C, due to the high levels of solar gain and contributions from other adjacent areas. Heat is distributed throughout the building by the process of thermal stratification, with the lack of natural ventilation further exacerbating the discomfort problems. Scale model studies were conducted re-affirmining the importance of solar shading devices. It was also found that most occupants in the northern area of the library were more comfortable than those in the southern areas. As a consequence of these findings a number of controls were suggested, including horizontal shading devices, the use of vegetation and landscaping, replacing existing glazing, the use of reflective surfaces and materials and the use of exaggerated building features themselves to provide additional shading. These changes were suggested in conjunction with improved more efficient lighting systems, improved ventilation in terms of enhancing the stack effect, and a solar collector facing south. Concluding that in Mexico there exists great potential for such comfort and energy saving projects.

The air movement and heat transfer characteristics of a Trombe wall channel solar passive system is examined by Chaturvedi (1992, #6080) to investigate its suitability for passive cooling applications. A thick south facing wall made of a heavy building material, such as concrete or stone, positioned directly behind single or double glazing, the air gap between these two walls acts as a convective channel forming part of a closed loop of a thermosyphon system that transports solar energy from the heated wall to the room. Estimates of approximately 50% of the solar energy gain by the storage wall is transferred by the airstream for immediate heating on a sunny day, while the remainder is stored in the wall for supplying the night time energy requirements. Using the "SIMPLE" algorithm, the author analyses the turbulent natural convection in the Trombe wall channel coupled to the room and explains how the system functions and outlines the physical processes and effects taking place within the channel and between the channel and adjacent room.

Gan (1997, #10556) has undertaken a similar study to investigate the natural ventilation properties of a Trombe wall by computational fluid dynamics (CFD). Depending on the ambient temperature, such a system can be adapted for daytime ventilation or night time cooling. Under conditions where internal summer conditions are warmer than external ambient conditions, due to high internal gains, then the Trombe wall can be used for summer daytime cooling as well. Gan used the finite TEAM code for CFD modelling, and validated his data against experimental data for enclosures with Trombe wall geometry's. Gan concludes that his experiments have shown that on moderate sunny days, Trombe walls can be used for ventilation cooling. To maximise this effect, the interior surface of the storage wall should be insulated. Additional vents should be provided to increase ventilation rates for high outdoor temperatures. Although Trombe walls were originally designed for winter heating, and therefore if ventilation cooling is the main objectiveGan suggestsa more effective strategy would be a solar chimney.

The accepted refurbishment proposals for the 1950's, 18storey GSW office tower in Berlin are outlined by Channer (1994, #8183). The tower is attached to a low rise office complex and has openable windows for ventilation. The proposals include the addition of a second single clear glazed skin to protect the west side from large wind pressures, creating a void which will act not only as an exhaust air plenum and site for the external shading elements but also as a buffer against heat loss and infiltration. To ensure adequate ventilation at all times, a mechanical supply system would also be needed, interacting with the double facade, which would still function as an exhaust chimney, with solar gain onto the shading elements, encouraging upward air movement. Refurbishment would include the addition of precast concrete planks, adding to the thermal mass of the structure. In the summer, the offices would be precooled at night, improving thermal comfort during the day, without the use of air conditioning. During the winter, the damping effect of the thermal mass would flatten any peaks in heating demand. The design was modelled using dynamic thermal simulation, CFD analysis and wind tunnel experiments and was found to perform as expected. From these results, compared to a similar model without the double facade, and with air conditioning the proposed building design reduced energy consumption by 27%. The combination of ventilated double facade and exposed thermal mass, provide good comfort levels, coupled with low energy use, the models predicted. The authors concluded that from the predictions, internal conditions are better than those in the existing tower, and wind driven ventilation rates are controlled by the sizes of ventilation openings equipped with limited automation to ensure that energy and comfort conditions are maintained.

4.1.1 Weather Data Investigations.

Tselepidaki and Santamouris (1991, #11158) propose a procedure for the statistical treatment of summer temperature data used for cooling, for Athens, Greece. Such data is vital for the evaluation of cooling systems, especially the ability to identify when passive or hybrid cooling technologies may be usefully and efficiently implemented. Experiments used hourly temperature data for the period 1977-1989 for Athens, which has a characteristically thermo Mediterranean climate with a wet period during the winter months and a dry hot summer period. Mean monthly summer temperatures vary between 19°C and 28°C. The Frequency distribution of ambient temperatures, revealed that they peaked at 14.00 hours, especially in July and August, with high frequencies of temperatures over 25°C occurring during these months between 09.00 am and 20.00 hours. An almost identical distribution was visible for temperatures over 28°C. No tendency of the temperature data could be found from their investigations. An attempt was also made to gain knowledge of persistence of hot and very hot hours, such data is vital in defining operational mode and the control of air conditioning units. As well as defining the limits of convective passive and hybrid cooling systems, and the prediction of the performance of ground to air heat exchangers. All of these procedures are outlined in more detail in the paper. The authors concluded by noting that their results indicate that the probability of hourly temperatures during summer being higher than 25°C is between 0.05 for October and 0.654 for July. For the temperature base of 28°C the corresponding probabilities are between 0.01 and 0.387. Their study referred to persistently high (25-28°C) temperatures for July and August, when cooling is necessary for more than five hours per day and more especially during the hours between 10:00-16:00.

In a similar study, Balaras et al (1993, #11155) investigated the dry cooling power index, for Athens. The Cooling Power Index represents the combined effects of ambient temperatures and wind on human comfort. A number of correlation's exist, but the authors have chosen to adopt the one suggested by Vinje, $H=20.52\ V^{0.42}(36.5-T)$ where H is the cooling power [kcal/m^2h]; V is wind speed [m/s] and T is the dry bulb temperature [°C]. Calculated H values relate to corresponding (hot, mild, cool, cold etc) experienced by humans based on a devised scale. The authors undertook a statistical analysis of the daily distribution of human sensations over a 13 year period, and an analysis of persistence. Specific details of these analyses are presented within the paper. The authors found that, based on the 13 year analysis the appearance of hot and mild conditions during a 24 hour period are significant during June/July/August and May/September respectively. Using the Eriksson probability model they also state this for hot conditions, the highest persistence for 10-12 continuous hours in July and August and similar values around 0.2 in June and September. They are significantly lower in May. The authors suggest that these conditions are of particular interest since they are directly related with the sensation of discomfort during the summer months.

A further study by Balaras et al (1992b, #11154) also attempted to define a cooling power index, but this time related corresponding sensations experienced by humans to a scale (hot<5, mild5<hot<10). Again calculations were based on meteorological data for Athens for a period of 13years (1977-1989) and for the months May to September. The authors used the Eggenberger-Polya and William's logarithmic series to accurately predict the probability of occurrence of varying length spells. In conclusion, the authors note that the Eggenberger-Polya model was found to represent the variations of the series of consecutive hours with mild conditions and William's model represented the conditions for the hot four series'.

4.2 Radiative Cooling.

4.2.1 Direct Radiative Cooling Strategies.

The use of plants on the surface of roofs absorb between 80-90% of short wave solar radiation, with only 15% being reflected, compared to 10-30% from conventional roofs according to a study by Eumorfopoulou and Aravantinous (1994, #8671). The depth of soil also acts as an insulation layer to dampen temperature fluctuations experienced throughout a day, as well as throughout a season. The density and height of plants also shields the building from wind fluctuations. The air trapped beneath the foliage and in the top layer of the soil, further insulates the building, slowing down the heat transfer from the building. The structure of the garden offers extra resistance during the winter to the thermo-transmission coefficient k, and therefore improving the its value. The author notes that research suggests that the coefficient of thermal conductivity of the wet soil is $\lambda=2.1$ W/m² K for light soil mixtures, typically used on the gardens of roofs, their coefficient of thermal conductivity was found to vary from $\lambda=0.5$ W/m²K to $\lambda= 0.6$ W/m²K. With no permanent water in the drainage layer the coefficient of thermal conductivity is calculated as being able to reach up to 0.4 W/m²K. The study has examined the roof under its conventional form and when planted. The planted roof contained 10cm thick drainage layer of embulged clay and a 30cm layer of planting soil for low plants. The study examined one roof fitted with no thermal insulating protection and one fitted with the addition of thermal insulating layer foam expanded polystyrole 4cm thick. With the maximum permitted coefficient of thermal transmission according to Greek regulations the k=value equal to 0.5 W/m²K, the calculations ranged from k=1.813 W/m²K for a conventional roof, to k=0.317 W/m²K for a planted roof with thermal insulation. Regarding its implications for passive cooling during summer, the study showed that according to the type of construction, its colour, form and material, roof temperatures can exceed 90°C. The green of the planted roofs helps to neutralise the thermal intensities during the day. The garden roof assisted in the reduction of the thermal differentiation's, with the temperature of the upper surface staying below 25°C. The authors conclude that, while this imaginative and luxurious solution is more complex and expensive than simply adding additional insulation to a conventional roof, it does prove that such ideas have their place, and if chosen, will provide an aesthetic as well as effective solution to the prevention of solar gains and thermal energy loss.

The use of a roof garden to cool the air above a building is also outlined by Gage's paper (1997, #10557) previously discussed in section 3.3.2 on night cooling.

The evaporative cooling effect of a roof lawn garden in Japan is the focus of an experimental and heat and moisture transport simulation study undertaken by Onmura et al (1994, #8391).Experiments were followed up with simulation to examine and predict the potential cooling effect. A 4mx9m sample, composed of lawn, planting-layer (non woven fabric) drainage layer and root intercepting layer, was set up on a real building, with outdoor temperature, relative humidity and solar radiation being measured every half hour. The use of non woven fabric instead of soil makes the whole structure lighter. Experimental results indicated that the evaporative effect does in fact provide a promising energy saving method. Similar samples were then measured in the wind tunnel, one had water supplied during the experiment and one was dry. Solar radiation was simulated by electronic lamps, with a corresponding wind speed of 1m/s. The temperature and heat flow rate were measured every hour until a steady state was achieved, after which the wind was changed to 2.0m/s and then 4.4m/s. The experiments were repeated without the addition of solar radiation, but with a heater located underneath the samples as a heat source. Surface temperatures of the lawn were then calculated by a simultaneous transport model of heat and moisture and compared to measured values. The air and lawn bottom conditions obtained from the wind tunnel experiments represented the boundary conditions. The results indicated that with regard to solar radiation a difference of about 3°C between the measured and calculated values were observed. The authors explained this as being by moisture transport due to the temperature gradient. In conclusion they noted that an evaporative cooling effect by a roof lawn during the summer was confirmed through field measurement. The follow up simultaneous transport model of heat and moisture were in good agreement with measured results obtained in wind tunnel experiments.

4.2.2 Indirect Radiative Cooling Strategies

Basic monthly weather data from the northern Mediterranean region is examined by Argiriou et al (1994, #10961) in order to study the radiative cooling potential of this region. By using measured hourly data over 12 years (from 1977-1989) for Athens, a detailed evaluation of the feasibility of using radiative cooling has been determined. This has been undertaken by examining the frequency distributions of parameters characterising the radiative cooling potential. The sky-temperature depression and the outlet air temperature for a flat plate radiative air cooler have been modelled using hourly ambient temperature, relative humidity, wind velocity, and opaque cloud cover (measured at 08:00, 11:00, 14:00, 17:00 and 20:00) data for Athens. Results compare well with other areas where the radiative cooling has significant potential. With the sky-temperature depression for Athens having a maximum of around 16-17°C for every month of the cooling season. The authors are aware that using hourly data for their predictions typically leads to an over estimating of sky temperature depressions and the performance of natural cooling techniques should be based on detailed climate data. The stagnation temperature is the lowest temperature attainable by a radiator for specific weather and operational conditions and indicates the cooling efficiency. Investigations have found that the lowest stagnation temperatures and highest cooling potentials occur during September and June. The contribution of a wind screen to reduce stagnation temperatures appears to be significant for optimal weather conditions. The stagnation temperatures of the unprotected radiator range from 22°C in September to 27°C in July for 80% of the time. For the wind screen radiators it ranges from 19°C in September to 23°C in July. Based on these results the authors found that the probability of observing poor radiator performance, due to cloudiness, is small. Regarding outlet temperature, the average temperature drop is about 3°C because cloudiness in Greece during the cooling period is very small. This verifies the findings that the use of wind screens for Athens is not recommended, because of their high cost and short life. Finally the authors conclude that radiatve cooling potential for Athens is useful.

In a similar study Argiriou et al (1993, #10960) focused on Southern Europe, using similar data and techniques they examined the potential for radiative cooling around the northern part of the Mediterranean basin, using weather data from 28 southern European and Southeastern United States locations. Results indicated that Athens was the most appropriate site among the ones examined, for radiative cooling applications, because the sky temperature depression rarely falls below 14°C. The mean daily useful cooling energy delivered by a flat plate radiative cooler at the various southern European locations ranged from 55 to 208 Wh/m^2 for average sky conditions and between 68 and 220 Wh/m^2 for clear sky conditions. For the US locations, corresponding values were 41 to 136 Wh/m^2 and 69 to 182 Wh/m^2 respectively. The authors therefore concluded that, based on their results, southern Europe exhibits a promising potential for the use of radiative cooling. Compared with the Southern US where weather conditions limit the use of radiative cooling and such processes would be relatively inefficient.

Tselepidaki et al (1993, #11153) also discusses the need for quality weather data, especially for the design of passive and hybrid cooling systems and techniques. Such information includes night cooling degree days, detailed daily variation of temperature information, the 24 hour distribution, the maximum and minimum values and the frequency distribution of the temperatures. The author presents a methodology on the treatment of the summer temperature data, based on multi year summer temperature data for Athens. Characterised by a warm Mediterranean climate, with mild but relatively wet winters, and warm dry summers. Mean monthly ambient temperatures are between 9-27°C, occurring January and July to August. September is also included as part of the cooling season due to unfavourable wind conditions, leading to high daytime temperatures. Other temperature parameters are outlined by the authors, for example the choice of sample weather data year (from 1977 to 1990), which is compared with previous sets to identify any trends. Results indicate that monthly cooling degree hours can be predicted accurately and has a function of the mean and mean maximum monthly temperature. The authors outline several expressions to calculate monthly degree hours. They conclude that the work outlined in this paper, examines summer ambient temperatures for Athens, and provides expressions to estimate the required information necessary to undertake design of passive and hybrid cooling techniques and systems.

4.3 Evaporative Cooling

Givoni (1992, #6454) defines the comfort zone as the range of climatic conditions within which the majority of people will not feel uncomfortably hot or cold. He suggests that there are some problems associated with some comfort standards, in particular, some do not account for the level of occupant acclimatisation within a region and are therefore prepared to tolerate higher temperatures than in other parts of the world. Givoni further discusses the use of Bioclimatic charts and how they would be useful in helping to establish ventilation guidelines is such regions. He outlines those proposed by Olgyay as well as his own Building Bio Climatic Chart (BBCC) which is based on indoor temperatures of buildings. The author examines the effects of acclimatization and standard of living, graphical demarcation of design strategies and acceptable conditions under still air, of particular interest is his discussion of direct and indirect evaporative cooling strategies. Direct evaporative cooling strategies reduce the air temperature by approximately 70-80% of the wet bulb temperature. Such evaporative cooling performs better with a large wet build temperature depression, characteristic of hot dry climates. This method involves high rates of outdoor air flow, due to the high humidity of the cooled air, with the indoor air and temperature of the surfaces are determined by the temperature of the cooled air. The author suggests that direct evaporative cooling is most applicable in developed countries, only where and when the wet bulb temperature maximum in summer is about 22°C and the dry bulb temperature maximum is about 42°C. Under such conditions, air leaving the cooler will be about 26-27°C, and the average indoor air temperature would be about 27-29°C. The comparable temperatures in hot dry countries, taking into account acclimatization, would be 24°C (Wet bulb) and 44°C (dry bulb).

For indirect evaporative passive cooling strategies consist of shaded water pond over an uninsulated roof, for example. The roof in this case would need to be insulated during the winter. The water temperature of the pond compares well to the ambient average wet bulb temperature, depending upon elevation and depth. The space under the pond is cooled by radiant convective cooling, reducing the indoor and radiant temperatures without increasing relative humidity. The author suggests that it is possible to apply this form of cooling in places where the maximum wet bulb temperature is higher by about 2°C than for direct evaporative cooling. The climatic limits of this form of cooling are slightly different, for hot developing countries the maximum wet bulb temperature of 24°C and maximum dry bulb temperature of 44°C.

Kruger and Mathews (1992, #5810) undertook a similar study, in which they while many countries used thermal standards, they often neglected to specify a minimum environmental control system, which resulted in thermally efficient buildings, but ones that did not provide adequate thermal comfort for its occupants. Kruger and Mathews note that no norms currently distinguish between different environmental control system (ECS) types or prescribe the minimum ECS to provide thermal comfort in particular climates. Therefore they focus on determining a set of norms to aid thermal comfort design, based on existing thermally efficient reference buildings, rather than on purely theoretical considerations. Simulations using the QUICK thermal analysis computer program were undertaken to examine the interaction between comfort, ECS climate and building design. Norms are determined by moving an hypothetical reference building to a certain summer climate. Comfort criteria associated with the specific building and internal loads are simulated. The thermal performance of the reference building, assuming 5 ach, for natural ventilation is then determined. The results are compared to thermal comfort ranges for the climate, and a determination is then made whether or not the simulated control strategy would provide the desired level of comfort. Using this technique a picture can be built up of the typical control strategies, that would provide comfort for the particular climate. Thereby determining the norms for a particular climate. The authors conclude, that the proposed method, while easy to use, is comprehensive and allows design freedom by not restricting the thermal characteristics of individual building elements. The authors suggest that this corresponding extra effort for design, can be offset by savings in life cycle cost.

4.3.1 Direct Evaporative Cooling Strategies

Direct Evaporative cooling systems humidify the air by water sprays, jets or wetted materials. The exchange of latent heat from the water, cools the air temperature. The theoretical limit of cooling by evaporation is when the Relative Humidity reaches 100%.

Kimura (1991, #6306) outlines both direct evaporative cooling of the air itself, and surface indirect evaporate cooling for hot humid regions. Although such strategies are generally more effective in hot dry regions than hot humid regions in terms of total amount of cooling, but in terms ofimproving the level in thermal comfort they may be as effective as each other. In hot dry air moisture is absorbed by the air, thus lowering its temperature, this can continue until thesaturation point of the air is reached. As moist cool air enters a space it slows down the transfer of moisture from the body, because the air is less able to absorb sweat, making the body feel cooler. This effect is more noticeable when the air is moving and when the skin is already wet. In stationary air, evaporation is slow by skin diffusion as sweat accumulates on the skin surface. As the air speed increases and flows along the skin, evaporation will take place, and the person will feel it as a comfortable breeze. Intermittent air movement will make a person feel more comfortable than air moving at a constant speed. Therefore, two processes exist, the use of evaporatively cooled air for urban and inside spaces and sensible cooling of inside surfaces by evaporative cooling on outside surfaces. The author briefly examines the theoretical energy balances involved in these processes, and concludes that the reduction of green areas has lead to a rise in ambient temperatures. This can be reduced by the introduction of foliage and water surfaces to aid the heat loss by evaporation, thereby avoiding excess accumulation of heat within the massive ground surfaces. In such areas, roofs could also be better covered with surfaces that aid evaporation. This process would have the resultant effect of reducing interior temperatures as the ceiling surfaces became lower.

Severalpassive cooling systems, applicable in hot and moderate climates are discussed by Ayoob et al (1994, #8380). Using validated mathematical models they simulated the performance of these systems in a test cell. Tested were a variety of shading options, for different orientation of slats at different rates of local renewable air and thermal mass. Experiments were also conducted for night time ventilation in low and high mass structures. The use of direct, regenerative evaporative cooling, as well as radiative cooling, was also tested. Results indicated that evaporative cooling systems, with different modes of applications besides shadings show a very effective performance, in particular in high inertia buildings in hot arid regions. Radiative cooling is also an efficient mode of cooling. A combination of systems and modes of operation should compliment modern architectural design and improve the thermal comfort of buildings in these areas.

Yoklic et al (1994, #8658) discusses the thermal performance of an office located in Gaborone, Botswana. The climate of this region is characteristed as dry subtropical (semi desert), during the warm season, temperatures can reach 79°F (26.1°C), while in winter 55°F (12.8°C) is typical with an occasional frost. The 18.000 square foot (1672.2m^2) building, is divided into four zones. Built from steel frame construction, with specialised prefabricated roof and wall panels, the ground and first floors are composed of concrete and additional building mass is provided by soil block internal walls. The design includes passive and hybrid interior and exterior thermal damping devices and passive downdraft evaporative coolers. Simulation results indicated the need for seven cool towers, located to provide the desired airflow through the specified zones. The evaporative cooler size was determined based on the yearly operating costs, and the cooling towers were then sized to more than meet these requirements. Additional shading and thermal control was recommended for the west facing zone and an active evaporative cooling system replaced the cool tower in zone A, in order to provide adequate and uniform cooling to an office block with a northern exposure. In conclusion, the authors noted that the use of the energy performance model (CalPas3) used in this investigation provided valuable and useful information. Simulation exercises reduced the thermal performance baseline to 34.9 /KBTU/ft2/Yr (396.5 MJ/m^2/yr), compared to 70.0 /KBTU/ft2/Yr (795.2 MJ/m^2/yr) which represents the average for commercial buildings of this scale in this region. Furthermore, the addition of more energy conservation improvements, such as the use of internal mass, and down draft evaporative cooling towers, managed to reduce further this figure to 21.9 /KBTU/ft2/Yr (248.8 MJ/m^2/yr).

Mansour et al (1997, 10608), uses computational fluid dynamics (CFD) to model a similar passive downdraught evaporative cooling tower such as used by Yoklic above. The paper concentrates on the interactions within the evaporative zone, and it is this that has been modelled using CFD. The paper focuses on the CFD model and its set up procedure, concluding that favourable results have so far been achieved for the section modelled. Once properly investigated, the authors aim to model a full 3D passive downdraught evaporative cooling tower, with wind catcher and occupant delivery sections.

The use and efficiency of evaporative cooling systems in French offices has been simulated by Millet (1990, #4264) (1990, #10877) and Picard and Millet (1992, #6904). Offices were located in Trappes, Agen and Nice. Air conditioning was used in some buildings, although the authors note that evaporative cooling systems can be used as an alternative. Two typical reference buildings were selected, differing only by their thermal inertia and the amount of solar input they receive. Other factors such as volume (5000m^3), office area (1500 m^2), North-South orientation, Coefficient of volume losses through walls G1=0.5 W/m^3 °C, controlled mechanical ventilation, and a scenario of occupation and internal heat input were the same. Several alternative cooling systems were studied by simulation and compared to the reference case. A non cooled building; double flux with humidification of exhaust, and a double flux with humidification of the exhaust air and fresh air. Further details of these systems are outlined by the authors. Occupant comfort criterion was calculated using both the PMV and PPD indices. The authors used ASTEC 3 software described as an algebro differential system solver developed initially for the description and simulation of electric circuits.

They found that, for the three weather stations, the most efficient system was system the double flux with humidification of the exhaust air and fresh air. More detailed results for each weather station are given by the authors. Experiments were then undertaken to verify the simulation results. The building consisted of 25 unoccupied apartments on five floors. On three floors of the building the air network was used to distribute air from a central unit equipped with a double flux system with exhaust air humidification at a rate of 4 office volume/h. The top and bottom floors were not cooled. The authors noted that in the pilot building, located at Senlis near Paris, results of experiments of this system were in good agreement with simulation results.

4.3.2 Indirect Evaporative Cooling Strategies.

The operation of an indirect evaporative cooler, equipped with a flat heat exchanger has been simulated for a typical building located in Athens by Klitsikas et al (1994,#8390).Air from the space is drawn over the wet plates of the heat exchanger, evaporated water is carried through with the air and discharged to the outside of the building. Fresh air moving past the dry side of the plates is then cooled before entering the room without any increase of its humidity ratio. Manufacturers data tables were used to calculate the cooling power as a function of the ambient temperature, indoor air temperature and relative humidity, enabling the outlet temperature to be calculated. Simulation exercisers were undertaken on a 300m^3 building, to asses the impact of the cooler on the behaviour of the building. Results indicated that the presence of the cooler increases the average monthly comfort hours per day. During the summer, July and August the average number of comfort hours fell to 4.3 compared to 13 during September, indicating that during this period the presence of the chiller is essential. The introduction of night cooling increased the amount of comfort hours per day. Results for various south facing window areas, was only studied for July, with the remaining months expected to remain unchanged. The effects were seen as negligible on the comfort hours for both cases, with cooler and for both 1 or 10ach. To conclude the presence of the cooler did increase the mean monthly number of comfort hours of the building. When the cooler was in operation the indoor temperature is much lower than in free floating conditions, especially when the free floating temperature is higher than 30°C, the indoor temperature may be reduced by 8°C during the day and 10°C during the night. The indoor temperature decreased is reduced when the ambient temperatures are low of when night ventilation is applied. When the cooler was in operation the indoor temperature did not exceed 32°C. The use of night ventilation increased the number of comfort hours in the day.

The use of chilled beams as a system for passively cooling buildings is outlined by Arnold (#10306, 1996).He explores their use in naturally ventilated buildings in the UK. Examples were taken from installations in both Sweden and Switzerland, where chilled beams and ceilings have been used in naturally ventilated buildings, with mechanically chilled water inlet temperatures as low as 14°C. However, Arnold notes that in the UK, chilled beams are usually installed as part of a mechanical system, taking the place of an indirect space cooler. Ventilation systems are usually designed to dry the air enough to reduce the dew point of air in the space to about 2K below either the temperature of the coldest surface of the cooling element, or the temperature of the chilled water. Minimising the associated risks of condensation. Arnold describes four UK buildings, owned by one client, all with opening windows and two with mechanical ventilation. Despite all buildings suffering from summer overheating, the client did not want to install full air conditioning. The clients energy policy included statements such as “only use energy for cooling when really necessary”, “use the simplest technology” and “use water as the primary means of distributing cooling, not air” so alternative solutions to air conditioning was to install either fan coil units or chilled beams. The advantages of chilled beams include greater energy efficiency, low maintenance, self adaptive control. Disadvantages include the risks of condensation, lower cooling power, and limited experience in UK. Simulation exercises indicated that they were a possible option, while in terms if the clients environmental policy, chilled beams were the preferred option. They also offered a self adaptive control in terms of temperature, in that the rate of cooling reduces as the temperature in the space falls. The only real concern was the risk of condensation. At temperatures were condensation would not be a problem, the associated cooling effect would be negligible Therefore the designers decided to allow the formation of condensation, but provided detectors, condensate would then either be collected, or once detected, be prevented from continuing to form. Conclusions were based on the results of monitoring these buildings after the systems had been installed. They noted that the occupants quickly learnt to keep the windows closed on hot days and the users appreciated the provision of passive cooling systems. However, the researchers also discovered a number of system limitations including the fact that occupants would open windows when the internal temperature rose to approximately 27°C, regardless of the consequences, to obtain air movement. Although condensation was initially considered a problem, investigations after installation showed that the system worked well.

The impact of cooled ceilings, simulated by using the dynamic thermal analysis program, ACCURACY is described by Niu and Kooi (1993, #7878).Simulations of the combination of evaporative cooling with cooled ceiling for office building cooling. Have been performed and validated against experimental data. The cooling ceiling configurationextracts heat by both radiation and convection, and the existence of the cooled panel surface lowers the radiant temperature in a room. This research attempts to combine the thermal dynamic modeling of building elements and ceiling panels with each other and to integrate the thermal comfort indices in the calculation procedure. The mathematical basis for the model is outlined in the paper by the authors, as well as detailed example of an evaporative cooling simulation. In conclusion the authors note that ACCURACY gives good results when compared to climate room validation data. The application of the validated program for the numerical simulation of evaporative cooling of office buildings in combination with cooled ceiling systems shows a promising potential of this passive cooling system in the Dutch climate.

A desiccant and evaporative cooling (DEC) system outlined by Dehli (1994, #7986) aims to separate the cooling and dehumidification operations are by using a rotating desiccant wheel (dehumidification), evaporative coolers and a rotating heat transfer wheel (providing sensible heat exchange). The desiccant wheel, composed of silica gel reinforced with inorganic fibbers and formed into a honeycomb shape rotates, within the outdoor air stream to remove moisture. Moisture is absorbed by the silica, which increases the air temperature, which in turn is removed by the rotating heat recovery wheel. The evaporative cooler then humidifies the dried air to further reduce the dry bulb temperature. The heat, generated during dehumidification of the supply air is removed and transferred back into the reactivation cycle by the heat recovery wheel. In the heat exchanger, external heat energy brings the reactivation air to the required temperature for desorbing in the desiccant wheel. When in the desiccant wheel, the exhaust air temperature is reduced with increasing the absolute humidity. The device is designed to operate during both winter and summer for heat, humidifying and cooling and dehumidifying in the same way as a conventional air conditioning device. A comparison in terms of investment, operational and maintenance costs is presented as well as on the thermal and electrical energy consumption. Dehli concludes that results show that the DEC system with desiccant wheel operating in the winter season as a total energy recovery wheel in combination with cogeneration energy supply performs far better than the traditional air conditioning system it was compared with. Other figures quoted by the author include a reduction in water supply by 40%; total annual operation costs reduced to 50% and the annual heating energy consumption the DEC heat recovery system needs only 40%

of the conventional air conditioning system. The author finally states that the DEC systems can be designed and installed for the same as traditional systems, because the refrigeration compressor and cooling tower are no longer necessary.

In a similar study Lindholm (1997, 10597) estimates the energy consumption of an evaporative and desiccant cooling. The study is based on the number of hours when a given supply air temperature can be obtained by using these techniques. In arid regions evaporative cooling is used to cool the supply air down to the comfort temperature, achieved by humidifying the air stream in one or more stages. As the air humidity increases, its dry bulb temperature falls, because the heat necessary for evaporation, is removed from the air stream by the introduction of fine spray. The air can be directly or indirectly cooled in this way. The temperature of the outdoor air stream is then decreased by using a sensible heat recovery device. A combination of these two configurations can also be used. However the high outdoor humidity levels and demands on the indoor climate greatly influence the supply air temperature possible by using evaporative cooling. Desiccant cooling devices employ either solid (desiccant wheel) or liquid desiccant material. Dehli (1994, #7986) above outlined the operation of these devices. The author highlights a number of limitations to these devices, such as the reachable supply air temperatures depends upon the prevailing exhaust air condition. As long as information regarding the room temperature, sensible heat ratio and the effectiveness of components are obtainable, this enables certain supply air temperatures to be achieved determined by plotting such variables on a psychometric chart. If climate data is available it is then possible to calculate the number of hours when the combination of ambient temperature and humidity is in each psychometric area. From this the corresponding yearly figures can be calculated, and a determination made regarding whether the ambient climate restricts the use of such devices or not. The author notes that addition humidification can lift the restriction of climate. In conclusion the methodology described in this paper, can provide a rough estimation of energy consumption expected for air conditioning when using evaporative and desiccant cooling systems. It should also be possible to estimate the regeneration heat load by using limit lines for different thermal coefficients or performance. Although the total regeneration heat demand is still dependent on the number of hours desiccant humidification is necessary, which is arid climates may be negligible.

4.4 Earth Cooling.

Mihalakakou et al (1995, #10898) study the effects of direct earth cooling in order to validate a model to predict the heat flow to the ground and the ground temperature at various depths beneath a building. Several calculation models exist to predict the ground temperature under a building, based on analytical solutions, numerical analysis and experimental measurements, example of these are given. The current study however, focuses on the complicated thermal process in the ground under a building and especially with the heat flow through the foundation. Mihalakakou describes the algorithm used in the investigation and the determination of the individual components, as developed within the TRNSYS environment. This is a transient simulation program with a modular structure which facilities the addition to the program of other mathematical models not included in the standard TRNSYS library. Two experiments are described, conducted during summer, each lasting 20 days. Soil temperature was measured to a depth of 0.3m in 5mm intervals below the surface and under the foundation of the building being studied. This data was then compared with theoretically derived data from the model, for both experimental and modelled ground temperatures the building characteristics outlined below were identical. The floor and external walls of which are made of 600mm dense concrete, 40mm expanded polystyrene insulation and 60mm dense concrete. The thermal conductivity of the concrete was found to be 1.4W/m°C and the conductivity of the insulation was 0.03 W/m°C. The ambient air temperature during the experiment fluctuated between 9.8 and 39.3°C. Comparisons of the data showed that they were in very good agreement with each other, providing a set of validation data for the model.

The use of an basement integrated into the passive cooling strategy for a Swiss office building is described by Lachal et al (1991, #6313). The 19th century building was renovated into offices in 1989, includes wide and deep cellars, for about 10m underground, the total volume of which is approximately 300m^3. Typical outdoor summer temperatures can reach 30°C, and therefor even with good insulation, the top floor can reach 28°C. The building was monitored before and after the introduction of the passive cooling system, by forty channels measuring temperatures, humidities, solar radiation, air flow rate electrical consumption etc. The study focused of the largest cellar, supplying the most overheated office with cool air. Results showed that good comfort was achieved by using this passive cooling system. The system was then modelled, in order to study in greater detail the effects of specific components on the operation of the whole system, which incorporated a cellar (the cooling source), the duct and fan (means of air transfer), and the south west office (the place in need of cooling). The author emphasized several considerations when using such underground locations for ventilation provision; clean, fresh and contamination free air. The building needs a very good insulated roof to reduce solar load, very good solar protection and good thermal interia with good thermal coupling between the thermal mass and inside air, and it also requires space to install the ducting throughout the building. The ducting should allow no depressurisation, be well insulated in warm weather and include a good fan, having an external motor. In conclusion such a passive systems can provide good comfort, at half the investment and 25% of the operating costs than a none passive system. The author also suggests that other cooling sources such as underground water could be used in this way.

Jacovides et al (1996,#10957) states that the use and prediction of direct or indirect earth coupling techniques for building engineering, requires detailed knowledge of soil temperature profile, as well as information about the diurnal and annual variation of soil temperature at various depths. Such measurements are spatially and temporally limited, and existing data depends upon local meteo-climatic conditions and soil properties. Models already exist to predict the earth's temperature as a function of depth, season and soil properties. Such data for these models requires information specific to the area in which a development is planned. The author uses the 74 year record (1917-1990) of ground temperature measurements obtained for Athens, through the Fourier technique. From the study the authors conclude that soil temperatures and their minima/maxima at different depths and at any time can be estimated on the basis of their annual periodicity with the help of harmonics computed by the Fourier technique. The first three harmonics taken together provide good agreement between the estimated and the observed soil temperatures at the surface as well as at various depths.

The cooling potential of earth-to-air heat exchangers is outlined Mihalakakou et al (1994, #10904) and (1994, #10903) consisting of buried pipes through which air is forced, consequently cooled by heat transfer with the surrounding soil mass. On exit from the pipe the cool air is then introduced and mixed with room air. Models exist to predict the transfer of heat and mass in soils under a temperature gradient, most of which consider a axially symmetric heat flow into the ground, neglecting the natural thermal stratification in the soil which alters the symmetry. The present study investigates the energy potential of these earth-to-air heat exchangers under real climatic conditions in Greece andattempts to determines their feasibility. Results will be presented in such a way as to be suitable for designers. A parametric study was first conducted, using a wide range of input variables, such as tube length and diameter, the depth of placement of the exchanger and speed of air flow etc. The performance of a plastic pipe of 0.125m in radius, 30m in length buried in the ground at about 1.2m guiding air at a speed of 5m/s was simulated, over

June, July, and August, using hourly values of the air and ground temperature from 09:00 hours to 21:00 hours, between 1981-1990. The analysis showed the cooling potential of these devices, operating during the summer, is important. It was also found that increasing the pipes radius represented a reduction of the convective heat transfer coefficient, resulting in higher air outlet temperatures and consequently a reduction in potential cooling capacity. At higher air velocities a slight increase in outlet air temperature was experienced. The convective heat transfer coefficient also increases, leading to a more efficient heat exchange, although the temperature increase at the pipe outlet is mainly attributed to the increased mass flow rate. In conclusion, the authors note that there is a considerable increase of the system cooling capacity potential with depth. A set of curves have been generated, usable by designers, in order to asses the use and potential of earth-air heat exchangers in Greece.

A range of passive cooling technologies involving natural heat sinks are discussed by Agas et al (1991, #10906), in order to provide comparative information regarding the influence and performance of night cooling and ground cooling via earth-to-air heat exchangers and direct and indirect cooling systems. Sensitivity analyses where used to establish the relative influence of each technique. The building was located in the Athens region, experiencing warm Mediterranean climate, with mild and relatively wet winters and warm dry summers. The thermal simulation was conducted, using CASAMO-CLIM (developed by Ecole Nationale des Mines de Paris, France) which was developed especially for cooling, and validated against real buildings. Four different types of passive cooling configuration were simulated, (a) earth-to-air heat exchangers (b) direct evaporative cooling components (c) indirect evaporative cooling components and (d) night cooling. Ground cooling simulations consisted of 50m horizontal PVC pipe of 0.2m diameter, with a fan at the inlet to circulate ambient air at a rate of 5m/s underground. This air was then introduced into the building. The optimum depth of the buried pipe, is an important issue, several positions were simulated from 1.5m to 6.5m deep, with the maximum indoor temperature decrease observed at a depth of 4m in June and 5m for July and August. At night the outdoor air temperature is often cooler than the air being circulated through the ground ductwork, therefore a control system is required which regulate the operation of an earth to air heat exchanger linked to the building. Results agreed with Mihalakakou et al above, in that increasing the length of the exchanger from 50m to 70m resulted in an indoor temperature drop of 0.5°C. While increasing the diameter of pipe from 0.20 to 0.22m resulted in a more significant reduction in indoor air temperature of 15°C. Reducing the airflow velocity, reduces the cooling energy offered to the building, leading in higher indoor temperatures.

The study also considered a parallel-plate pad evaporative cooler, and indirect evaporative cooling system. Regarding night cooling, the authors considered that the building was ventilated between 23:00 and 07:00 hours, using a variety of ventilation rates between 2 and 8ach with a step of 2ach. Indoor temperatures are reduced by increasing the ventilation rate, although the maximum depression of the peak indoor temperature does not exceed 1°C. The decrease in indoor temperature is more important during June and August and less so during July. However, the authors conclude that while night ventilation can contribute to the cooling of the building, it is not sufficient to produce acceptable temperature levels during the day and therefore additional cooling should also be installed. The authors also conclude that the optimum depth for an earth-to-air heat pipe is between 3.5 and 5m, increasing its depth has little additional cooling advantage. The fan rate of the cooler is more important than the flow rate of water in direct evaporative cooling systems, and finally with indirect evaporative coolers, acceptable indoor air quality can be achieved during June and August with an air speed through the cooler of 0.1m/s, however during July, an higher air speed of 0.3m/s is required.

Several similar studies to those highlighted above have also studied buried pipes to cool buildings these include Santamouris et al (1995, #10899) (1995, #10901), Mihalakakou et al (1993, #10910) and Mihalakakou et al (1992, #10896), (1995, 10902).

5.0 Conclusions

The use of passively cooled buildings has clearly been demonstrated, indeed, strategies such as evaporative, radiative and night cooling for example, incorporated into modern buildings within these regions have adapted over many years. Designers within these regions make use of the building form, its location, colour, surrounding vegetation, and sparse water supply, to aid cooling and more importantly, they are aware of the strategies' limitations.

In temperate climates, night cooling, thermal mass, desiccant cooling, buried earth pipes, and chilled ceilings in naturally ventilated buildings are all being used. The overriding point echoed by researchers is that these systems must be designed and installed with care. Over cooling by chilled ceilings in naturally ventilated buildings, and over cooling using night ventilation can not only lead to thermal comfort, but also moisture problems. Therefore many of these systems have been developed to incorporate a level of mixed mode or hybrid operation. Intelligent controls and the use of fuzzy logic help such systems effectively operate.

A number of computer simulation programs have been developed as tools and design aids (PASSCOOL and NITECOOL) to help architects and designers understand and model passive cooling and solar buildings. The main advantage is that they enable such building professionals to change their designs and see almost straight away their results. They can also model a number of designs, under different climatic conditions and in a number of locations. The improvements in computing power, its availability and cost in recent years has meant that such design aids are extremely common place and provide a very cost effective means of pre design feasibility study.

Current limitations of passive cooling and natural ventilation will undoubtedly lead to more innovation and the further adoptation and mutation of traditional passive cooling technologies as they are combined with modern mechanical assistance.

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AIVC Air Infiltration and Ventilation Centre

The Air Infiltration and Ventilation Centre provides technical support in air infiltration and ventilation research and application. The aim is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.