GOOD PRACTICE GUIDE 291

A designer's guide to the options for ventilation and cooling

BEST PRACTICE PROGRAMME

ENERGY EFFICIENCY

GOOD PRACTICE GUIDE 291

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This Guide is based on material drafted by Ove Arup under contract to BRECSU for the Energy Efficiency Best Practice programme.

This Guide incorporates a series of checklists to support the recommended option appraisal method.

The checklists are listed below together with the relevant page number.

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1 INTRODUCTION

Annual energy consumption of air-conditioning systems in the UK service sector is significant; 55 PJ (1994) with an energy cost of £830 million leading to around 9 million tonnes of carbon dioxide (CO_2) emissions.

In recent years, there has been significant progress in the application of techniques which reduce the dependency on conventional air-conditioning – techniques such as natural and passive ventilation, mixed-mode operation and low-energy cooling systems.

This document provides a guide as to where these techniques might be used successfully and gives an indication of where the boundary limits are. It provides the designer with a systematic approach to evaluating the ventilation and air-conditioning options for a building, with a view to avoiding unnecessary use of conventional air-conditioning. Where it is unavoidable, guidance is given on good practice to ensure systems run in an energy-efficient manner.

In any application, ventilation and cooling strategies should be driven by the occupant and client requirements and should match the building's thermal characteristics. Naturally, this will have to work within the normal constraints of capital and operating cost – design is an iterative procedure in which these and other factors need to be balanced. A strategic approach to balancing these needs is covered in Good Practice Guide (GPG) 287.

The more environmentally friendly solutions, which employ the use of renewable energy sources with utilisation of wind and buoyancy forces for ventilation, thermal mass for heat gain attenuation, displacement ventilation and low-energy cooling systems, can be applied in many types of non-domestic buildings. However, there are limitations; they are not panaceas for all internal environment problems. This Guide identifies what the boundary limits are to assist in the development of the concept design.

This Guide concentrates on the ventilation and cooling strategies. Consideration of space heating is an integral part of this process but is addressed in GPG 182 and GPG 187 (see the back cover).

A 'sister' Guide for clients (GPG 290) has been written in parallel with this designer's Guide and provides a non-technical discussion of the issues addressed in this document.

2 HOW TO CARRY OUT AN OPTION APPRAISAL

Option appraisal is something which will happen as a matter of course in good design practice. It is an iterative procedure which attempts to balance the user requirements, the constraints of costs and environmental policy with the design of the building envelope and its services. In this process, the central criteria will be the users' thermal, aural and visual comfort and air quality requirements appropriate to the activities within the building.

The option appraisal method provides a systematic approach to evaluating the ventilation and cooling strategies. It provides a framework of checklists (in the appendix starting on page 24) and rules of thumb that define the key performance characteristics, energy and costs. The systems discussed in the Guide include 'low-energy' systems which have the potential for reducing the reliance on large, complex, energy-intensive heating, ventilation and air-conditioning (HVAC) systems.

The method provides a means of comparing parameters such as:

- the control of environmental factors
- space requirements for plant
- adaptability of space usage
- costs of systems
- energy use
- associated CO_2 emissions.

It provides a means of assessing the various options in a quantitative way using data based on broad assumptions and rules of thumb derived from calculations on a notional office (see preliminary notes to checklists). By careful use of the checklists and completion of the option appraisal worksheet, an accurate assessment of the ventilation and cooling options may be made.

The information in this Guide is based upon historic data and assumptions have been made on typical buildings and systems. As the design develops, building-specific detail should form the basis of the design analysis as it becomes known. See figure 1 and the worksheet overleaf.

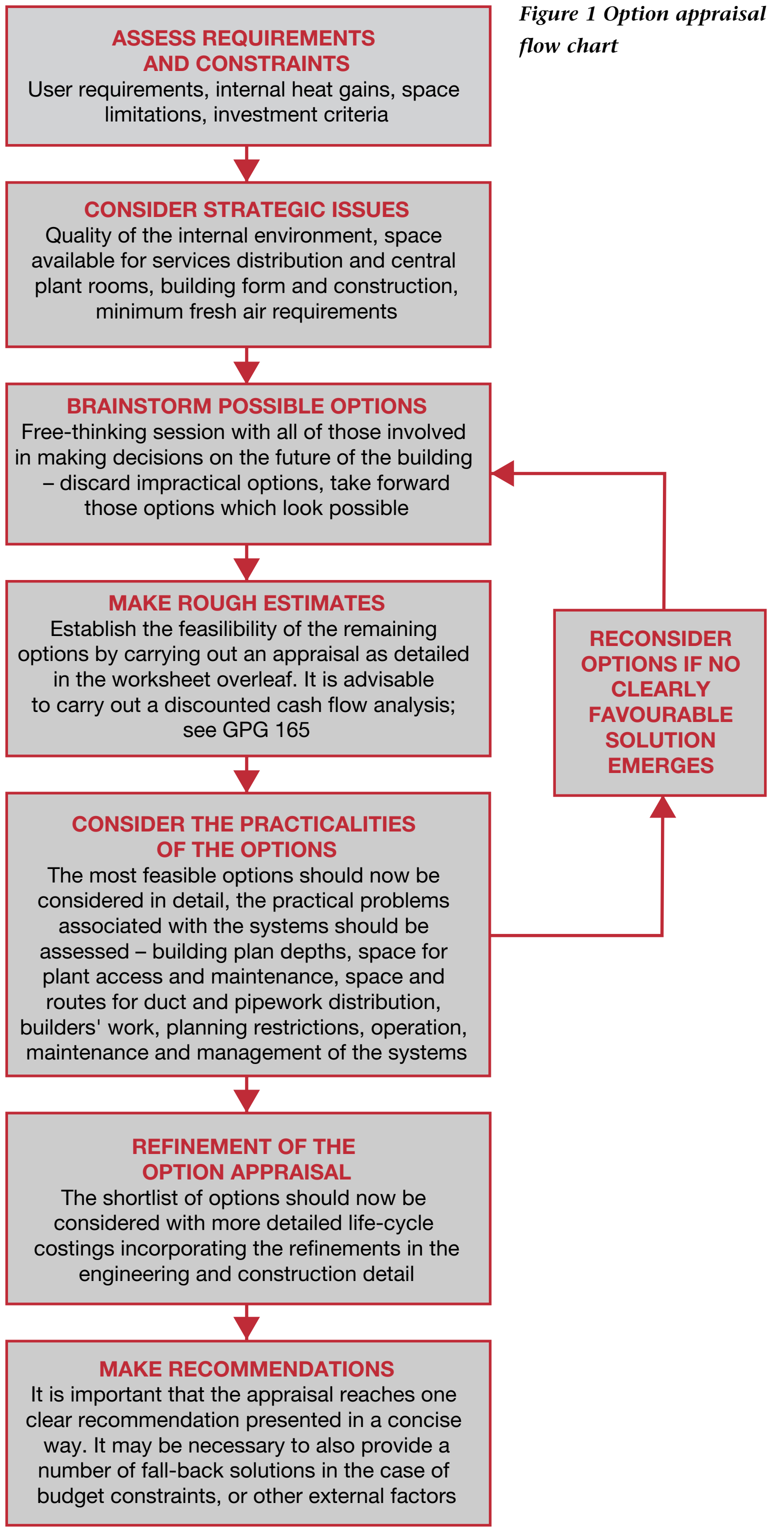


Figure 1 Option appraisal flow chart

HOW TO CARRY OUT AN OPTION APPRAISAL

OPTION APPRAISAL WORKSHEET – VENTILATION AND COOLING	OPTION 1	OPTION 2	OPTION 3
System type:			
ENERGY CONSUMPTION			
Fan energy (central and/or distributed)			
A Fan installed load in W/m^2			
B Number of equivalent fan hours during occupied period per year – checklists 3, 6, 7			
C Number of equivalent hours run of fan for night cooling per year – checklist 3, 6, 7			
D Annual fan energy kWh/m^2 $D = A (B + C)/1000$			
Pump energy (related to cooling)			
E Chilled water pump energy per year (kWh/m^2) based on equivalent hours run – checklists 6, 7			
F Condenser water pump energy per year (kWh/m^2) – checklists 6, 7			
G Other pumps per year (kWh/m^2) – checklist 6			
H Annual pump energy (kWh/m^2) $H = E + F + G$			
Chiller energy			
I Peak cooling load (W/m^2)			
J Number of equivalent chiller run hours at full load per year – checklists 6, 7, 8			
K Chiller seasonal CoP – checklist 9			
L Annual chiller energy (kWh/m^2) $L = I \times J/(K \times 1000)$			
M Heat pump energy, where applicable (kWh/m^2) – checklist 6			
Heat rejection			
N Fan energy per year (kWh/m^2) based on equivalent hours run – checklists 6, 7, 8			
Humidity control			
O Humidification energy per year (kWh/m^2) – checklist 6 (electrical)			
P Reheat energy per year (gas) (kWh/m^2) – see typical ECON 19 heating energy figures on page 34, checklist 6			
Q Energy costs for reheat (gas) ($£/m^2$) $Q = P \times (£0.0081/kWh)$			

HOW TO CARRY OUT AN OPTION APPRAISAL

OPTION APPRAISAL WORKSHEET – VENTILATION AND COOLING *(continued)*				
	System type:	OPTION 1	OPTION 2	OPTION 3
ANNUAL RUNNING COSTS				
R	Total ventilation and cooling energy (electrical) (kWh/m^2) R = D + H + L + M + N + O			
S	Energy costs for ventilation and cooling (electrical) (£/m^2) S = R × (£0.051/kWh)			
T	Total energy costs (£/m^2) T = Q + S			
U	Maintenance costs (£/m^2) – checklists 2, 3, 6, 7, 8 Consider also water supply and water treatment costs			
V	Total annual running costs V = U + T			
CAPITAL COSTS				
W	Capital cost (£/m^2) – checklists 2, 3, 4, 5, 6, 7, 8 Including the design and installation cost of builders work in connection with the ventilation and cooling systems			
OTHER FINANCIAL CONSIDERATIONS				
X	Simple payback period – but see GPG 274			
Y	Net present value (£) – see GPG 165			
Z	Internal rate of return (%) – see GPG 165			
CO_2 EMISSIONS				
AA	CO_2 emissions (electrical) AA = R × (0.46 kg/kWh)			
AB	CO_2 emissions (gas) AB = P × (0.19 kg/kWh)			
AC	Total CO_2 emissions AC = AA + AB			
OTHER ISSUES				
AD	Space requirements of plant and distribution systems (%) – checklists 2, 3, 4, 5, 6, 7, 8			
AE	Quality of the internal environment – checklists 1, 2, 3, 4, 5, 6, 7, 8			

Now refine your estimates on the most favoured options. The fan, pump and chiller loads should be entered by the designer and be specific to the building in question. Other information may be found in references given in the checklists for each particular system type, unless otherwise stated. Energy prices and CO_2 emission factors are appropriate for third quarter 1999 and may need to be adjusted to current rates.

3 USER REQUIREMENTS

The user requirements are largely fixed by the nature of current and anticipated business and activities – process load heat gain, occupancy hours, quality of the internal environment, local occupant control, management and maintenance expertise held by in-house staff.

The decision whether to use natural ventilation, mechanical ventilation or air-conditioning can be determined by addressing the following key questions about the building and its internal environment. Figure 2 presents a flow chart summarising these questions.

IS CLOSE CONTROL OF HUMIDITY NEEDED?

Humidity is measured in terms of relative humidity (RH). In general, people find the humidity to be acceptable between the ranges of 40% to 70% RH. If the humidity is too low, then problems with static electricity (<40% RH) and health problems associated with the drying of the respiratory tract (<30% RH) can occur. In many UK buildings during an average year the space humidity will remain within the comfort band for a large proportion of the year, with only minor excursions to excessively high humidities in the summer and low humidities in the winter. However, close control of humidity may be required for art galleries, protecting mainframe electronic equipment (although personal computers have wider tolerances), magnetic tapes or other sensitive equipment.

DOES THE BUILDING HAVE TO BE SEALED AGAINST NOISE OR POLLUTION?

Often a building can be ventilated from a façade which has no significant noise or pollution problems, for instance, at the back. This allows the designer to avoid heavily serviced solutions, including mechanical cooling, which are often the consequence of sealing the building.

DOES YOUR APPLICATION HAVE TO ACCOUNT FOR HIGH INTERNAL HEAT GAIN?

The internal heat gain is influenced by the occupancy density, computer and other machine loads and lighting loads. If these heat loads are high, it is worth considering reducing them. For example, there are many energy-efficient lighting devices on the market, high-efficacy lamps, high-efficiency luminaires and lighting controls. If these loads remain high, then some form of cooling will be required to the space, and natural ventilation may not be an option.

WILL IT BE ACCEPTABLE FOR THE OCCUPIED SPACE TO EXCEED 28ºC FOR A FEW HOURS EACH YEAR?

This judgement should be based on occupants' activities and all the other conditions in the space, such as air movement, radiant temperature and humidity. It should be noted that there is a correlation between high temperatures, high humidity and reduced productivity; however, this should be balanced against the frequency of these extreme conditions. A well-designed building envelope in the UK can restrict peak space temperatures to about 28ºC without the need to resort to mechanical cooling. If this temperature is acceptable to the occupants for, say, 1% of working hours, then a naturally ventilated solution may be a viable option.

This has been found to be acceptable in a number of buildings; an example is the refurbished Walton Hall administrative office at the Open University (GPCS 308).

The points raised above should be addressed in conjunction with various management and maintenance issues. In particular:

- the building and its system should be responsive to user needs and have the capacity to rectify circumstances when the occupants become uncomfortable
- occupants may have an increased tolerance to such conditions where they are able to take some personal action to ameliorate their situation, such as opening windows, adjusting controls, etc
- it is important that the system should be understood by its users, and maintained so that it can be operated correctly.

USER REQUIREMENTS

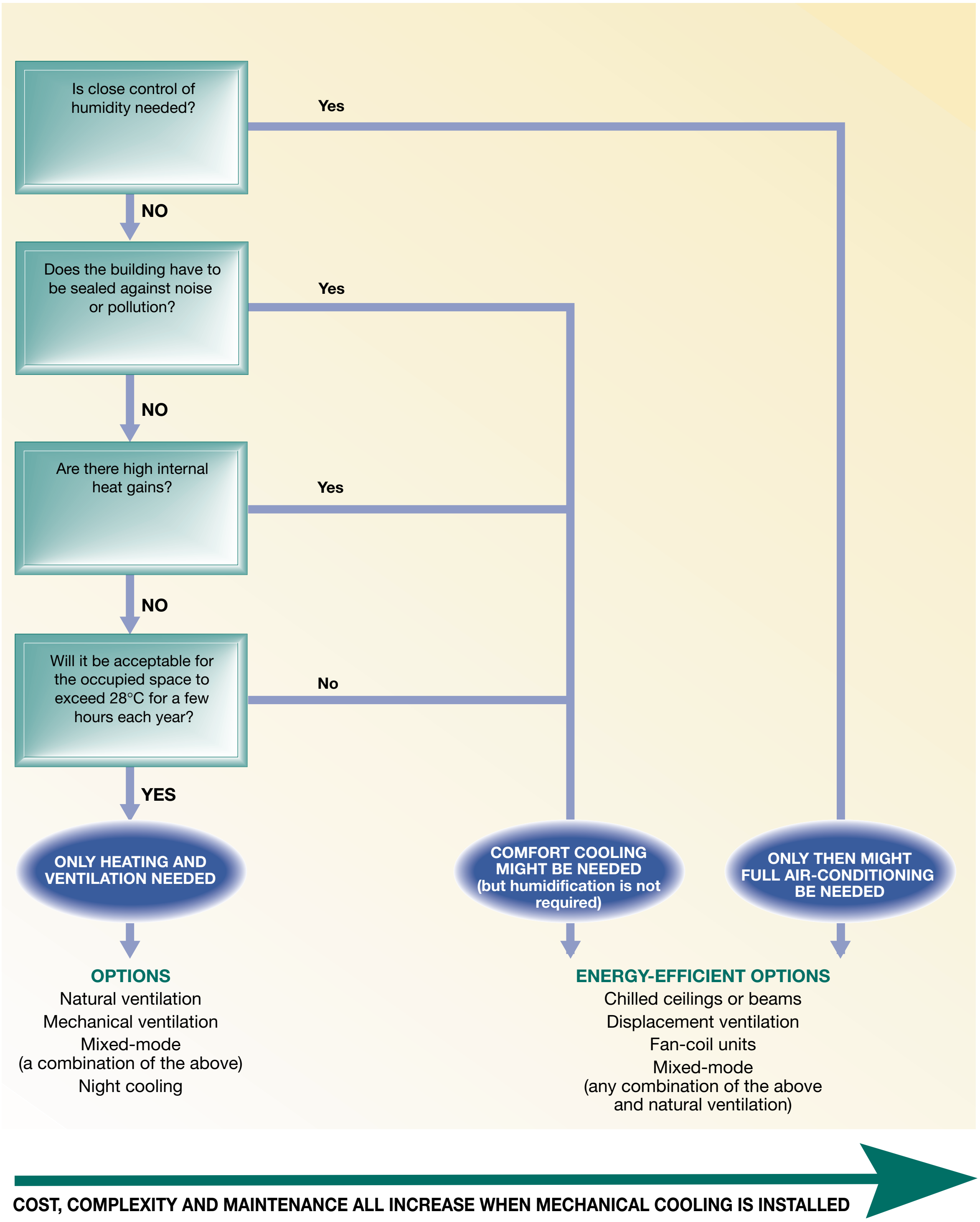


Figure 2 Flow chart on need for mechanical cooling

4 BUILDING THERMAL CHARACTERISTICS

The design of mechanical services pivots on the quality of the building envelope. If the thermal characteristics are good, then the services engineer's job is greatly simplified and the client benefits too:

- plant is smaller and less complex
- plant has a lower capital cost
- plant runs in a more stable and energy-efficient manner
- the systems are normally easier to understand, and therefore have a better chance of being operated and maintained correctly.

The building envelope should be the main climatic modifier which facilitates the use of strategies based on natural or mechanical ventilation. This involves consideration of the factors detailed in checklist 1.

Figure 3 The Body Shop headquarters at Littlehampton has an envelope that acts as the main climatic modifier between the internal and external conditions

5 VENTILATION STRATEGIES

Ventilation is necessary to control the level of pollutants inside a building; these contaminants take the form of gases, particulates and odours. The occupant will, in the majority of cases, detect the existence of objectional odours long before the concentration of the pollutant rises to constitute a health hazard. As a consequence, the ventilation rate is normally designed to control odour level in the space.

In the design of a ventilation system, minimum fresh air will be set to control odours mainly emanating from the occupants themselves, although fresh air volumes will need to be substantially higher where tobacco smoking is permitted. In addition, ventilation air can be used to provide a means of improving thermal comfort conditions during the summer by air movement or 'free cooling' whenever the outside air is at a lower temperature than inside. Such cooling will require a considerably greater air throughout than that supplied in winter.

More complex strategies involve the use of the storage effects of the building fabric to reduce peak daytime temperatures – this method has the potential to keep the internal temperature below that of the outside air without using mechanical cooling. Night-time ventilation can be used to cool the building mass, ready to absorb excess heat the following day.

5.1 NATURAL VENTILATION

Natural ventilation relies on moving air through a building under the natural forces caused by wind and the buoyancy effects of temperature differences.

The majority of the UK building stock is naturally ventilated using openable windows. This normally provides only coarse control of the flow of air. However, occupants tend to prefer these buildings to air-conditioned ones because they have individual control, they understand the system, and they have a system which gives an immediate response (see checklist 2).

Natural ventilation delivers low energy and low running costs but the consistency of the thermal environment may be lower than that achieved by mechanical means. Air paths need to be simple and generous as wind and buoyancy pressures are low.

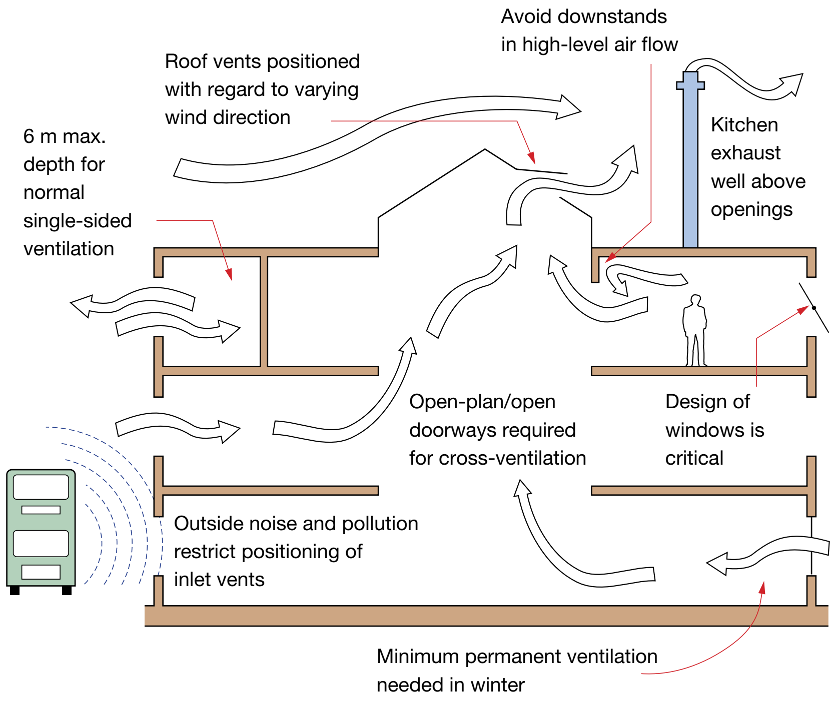
The three main categories of natural ventilation systems are listed below and illustrated in figure 4:

- openable windows (single-sided or cross-ventilation)
- motorised vent openings and night cooling (single-sided or cross-ventilation)
- stack ventilation and night cooling.

Even if the external temperature is higher than the internal temperature, the ventilation air may assist cooling of the occupants by increasing air movement. However, if thermal mass is used as a supplementary means of cooling, it may be better to revert to minimum fresh air and let the mass absorb the heat gain rather than bring in large quantities of hot outside air.

Natural ventilation can be used in a ventilation strategy which uses night cooling. This has the advantage of being able to depress daytime peak space temperatures by about 2ºC to 3ºC.

Figure 4 Modes of natural ventilation



VENTILATION STRATEGIES

Thermal mass is most effective when it is coupled with night cooling to dissipate heat absorbed by the room surfaces during the day. Outside air at cooler night-time temperatures is introduced during the unoccupied period to purge the building of the accumulated heat gain.

The external air must be at a lower temperature than inside the building in order to cool the mass. Control of this process is very important to avoid over-cooling and the subsequent use of heating to bring the building back up to a comfortable temperature for the start of the occupied period. Stack ventilation is driven by density differences between cool and warm air. It is enhanced by the use of thermal flues – these can take the form of specially designed appendages or they can utilise a building feature like an atrium, or stairwell; see figure 4. Security risks must be considered when windows, etc, are left open for night cooling.

Wind scoops originated over 2000 years ago in the Middle East, but tended to be orientated for a single prevailing wind direction. Modern versions generally have openings on all sides of the tower with automatically controlled dampers so that all wind directions can be exploited. Their main advantage is that the source of fresh air at roof level is likely to be relatively free from contamination or traffic pollution compared to that at ground level. The drawback is that performance can be compromised when wind and buoyancy forces are in opposition.

The Elizabeth Fry Building, University of East Anglia, uses a hollow core floor system

Airflow driven by wind and buoyancy forces is inherently energy efficient but, because it is dependent upon natural forces, the system performance is not as predictable as a mechanically ventilated system. Fans may be required to supply air at a high enough flow rate in order to cool the fabric down by the requisite amount. For a more robust system, mixed-mode (see section 5.3) may need to be considered.

5.1.1 Natural ventilation option appraisal

Capital and operating costs

- Capital costs of naturally ventilated buildings will be lower than those for air-conditioned buildings.
- These savings can be channelled into a higher specification for the building envelope, for example, increased solar shading and higher levels of insulation.
- Natural ventilation systems offer the lowest energy performance (see checklist 2). Operating costs are generally lower than those for air-conditioned buildings.
- Plant space requirements for natural ventilation systems are minimal, leaving considerably more lettable area than is the case with mechanically ventilated or air-conditioned buildings.

Absolute quality of the internal environment

During the summer months, the daytime temperatures within a naturally ventilated office would generally follow the external temperature. If the thermal mass in the building is cooled at night with outside air then the system can produce daytime temperatures inside the building, on average a couple of degrees lower than the external temperature; thereby the level of comfort for occupants is improved (see checklist 1).

- Naturally ventilated buildings will be influenced more by their surroundings than air-conditioned buildings. Hence, pollution and noise transmission problems have to be dealt with by avoiding the location of vents/windows adjacent to a busy road or an industrial site. If the building is on a rural site, high pollen levels may cause problems for some occupants.
- Internal odour level control is generally satisfactory in summer where large air change rates are used for thermal comfort. Care must, however, be taken to ensure odour level control in the winter months. There would be less air movement when the building is operating with less fresh air, usually at the discretion of the occupant. With the random nature of wind, guaranteeing a minimum ventilation rate without the intervention of the occupants is not possible. This can be achieved with mechanical ventilation, with additional capital and energy cost.
- Naturally ventilated buildings do not allow control over the internal humidity, although this is rarely a concern for occupants.

VENTILATION STRATEGIES

Environmental issues

- Naturally ventilated buildings require relatively low energy consumptions, particularly for electrical plant.
- CO_2 emissions should be very low, thus reducing the environmental impact of the building.

Flexibility for spatial layout changes or occupancy use

- Spatial layout changes can be accommodated readily where single-sided ventilation serves a depth of less than twice the floor to ceiling height.
- If cross-flow ventilation exists through a space, then any subdivisions of the space with partitions or substantial obstructions could radically affect the ventilation flow pattern. Where these are added during refurbishment, transfer grilles or alternative air paths should be set up.
- Stack ventilation can be arranged to serve deep cellular offices; the effect that spatial layout changes may have on the ventilation flow should be considered and accommodated in the design.
- Security can be an issue when designing for natural ventilation. It is generally undesirable to have accessible windows open, especially at night. However, openings for night cooling can easily be designed to maintain building security.

5.2 MECHANICAL VENTILATION

Mechanical ventilation systems have fans to supply and/or extract air to and from the building and can thus maintain specific internal temperatures more readily than natural ventilation systems which function under variable wind and buoyancy forces.

The three main categories of mechanical ventilation are:

- extract only
- supply only
- supply and extract.

See figure 5 on the right and checklist 3.

Mechanical ventilation is predictable in its operation; it permits coupling to heat recovery and filtration. If supply air is delivered to the space it also provides a means of distributing humidified air in winter, albeit at an additional energy cost.

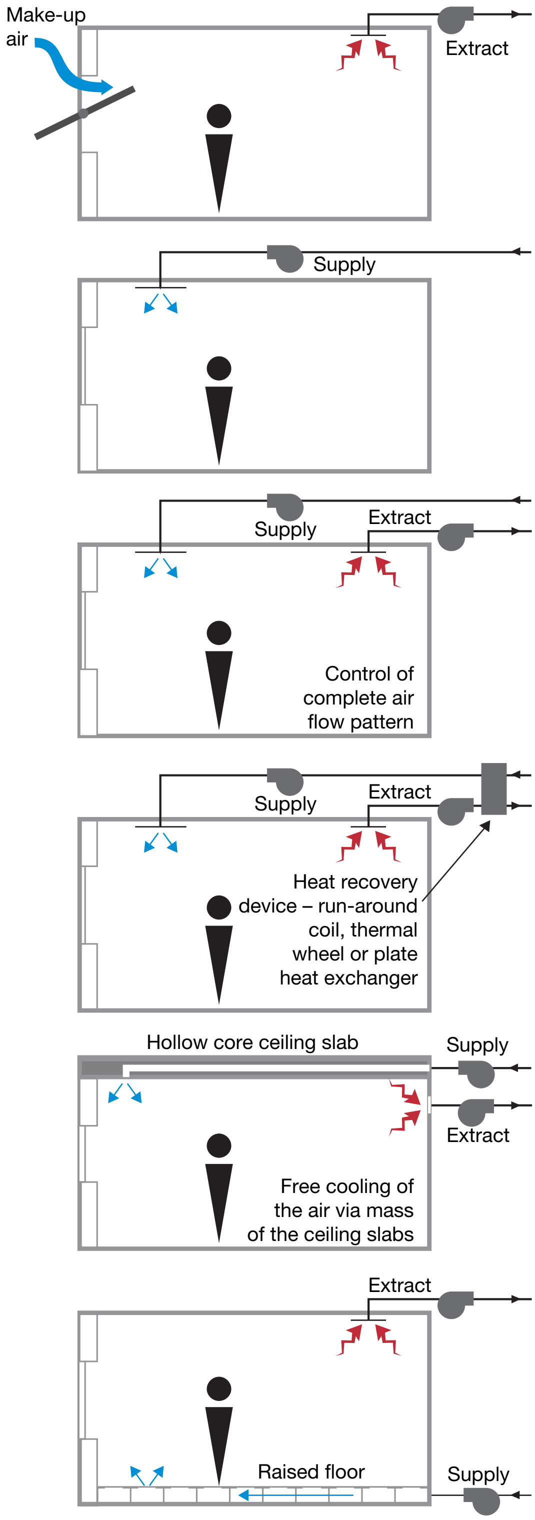


Figure 5 Mechanical ventilation options

Extract only – can be a local system or ducted

Supply only – pressurises room to avoid infiltration

Supply and extract balanced ventilation

Supply and extract with heat recovery

Hollow core supply – supply air delivered through ceiling slab

Ventilated floor void

VENTILATION STRATEGIES

5.2.1 Mechanical ventilation option appraisal

Capital and operating costs

- The capital costs are higher than for naturally ventilated systems due to the additional expense of air-handling plant and distribution ductwork.
- The air-handling plant will occupy considerably more space, thus reducing the net to gross floor area ratio.
- The operating costs are higher due to the electrical energy usage for the system fans – this should be minimised by designing to low pressure drops and operating only when absolutely necessary.
- The heating requirement for supply air can be reduced by devices which recover heat from the exhaust air – recuperators, thermal wheels, run-around-coils (see checklist 4). Figure 6 provides an indication of the amount of heat recovery possible. Temperature efficiency is a measure of the ratio of temperature differences across the heat exchanger in supply and exhaust air streams and varies according to the device (eg run-around coil: 55-60%; thermal wheel: 75%; recuperator: 55-65%). In assessing the effectiveness of such devices, the extra resistance they present to the air stream (and hence extra fan power required) should also be assessed. The energy cost of running the device and the extra fan power should be balanced against that of the heat energy saved, bearing in mind whether fossil fuel or electricity is being used or saved.

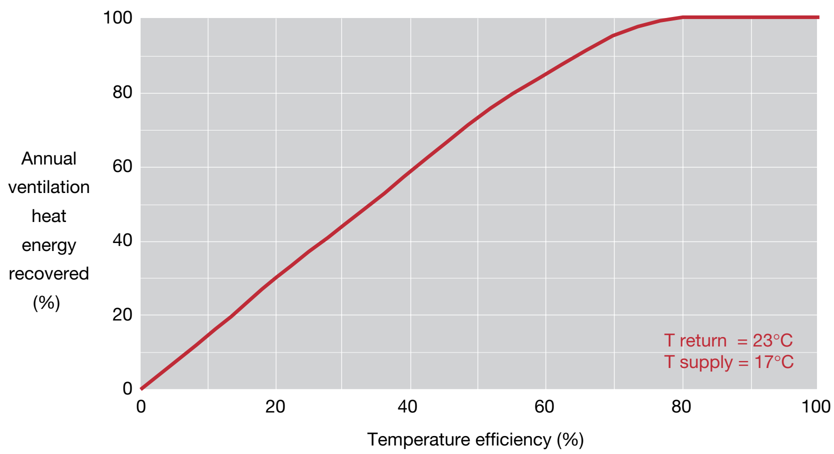


Figure 6 Graph of annual ventilation heat energy recovered vs temperature efficiency for mechanical ventilation

Quality of the internal environment

- These systems can be designed to perform in a very predictable way and are not affected by the vagaries of wind conditions.
- They can provide a filtered supply of clean air with low levels of particulates.
- They avoid the transmission of ambient noise into the building with an appropriately attenuated air supply system, although they generate noise themselves.
- Humidified air can be distributed in a controlled way, but at an extra energy cost.
- Unlike natural ventilation, the size of the air paths can be reduced as the pressure drop is not as critical. However, to reduce the fan power requirements, the designer should endeavour to keep the pressure drop of the distribution system to a minimum. Designers should aim for a specific fan power benchmark of 2 W/l/s and ideally for 1 W/l/s.

Environmental issues

- More electrical energy is used than with naturally ventilated systems, hence the CO_2 emissions will be higher, and consequently the building will have a higher environmental impact.
- Good design of the air distribution system will minimise the additional fan energy, eg low pressure drop air paths, high-efficiency fans and variable speed motors rather than dampers.
- Where humidification is employed, humidifier choice will influence internal environmental quality and energy consumption.

Occupant expectation

Occupants do not like loss of control over their ventilation, so they generally do not like sealed buildings with unopenable windows. Their expectation of the internal environment is often more demanding and their tolerance of system failure reduced.

Management and maintenance issues

There is more plant than with naturally ventilated systems, eg fans and filters, and ductwork systems need to be kept clean, hence maintenance costs are higher. In addition, more sophisticated systems, eg those with heat recovery devices or humidifiers, have greater maintenance requirements.

Flexibility for changes in spatial layout or organisational use

- The security of the building need not be impaired, as might be the case with opening windows when the system is operating on night cooling.
- Floor supply systems give good flexibility in accommodating spatial layout changes, as floor outlets can be moved to match occupancy patterns. High-level ducted systems have reasonable flexibility.

In summary, the penalty of mechanical ventilation is electrical energy usage for the system fans, which, from case study evidence, can be appreciable if not designed to low pressure drops and operated for only those periods when absolutely needed. In addition, occupants react badly to the sealing of a building and to the loss of control over their ventilation. Furthermore, capital costs are higher than for most natural ventilation systems.

5.3 MIXED-MODE VENTILATION

There are a number of ways in which the building can be operated with a mixture of natural and mechanical ventilation – this is referred to as mixed-mode, which exploits and aims to maximise the benefits of both systems. This type of approach may also use mechanical cooling for peak summertime conditions (see checklist 5).

Zoned systems can have, for example, natural ventilation on the perimeter and mechanical ventilation in the core. This design strategy could also be used where there are specific areas with high heat gain.

Changeover operation uses different systems for different times of the year. For example, during the winter the building could be sealed and mechanical ventilation used to supply minimum fresh air. Exhaust air heat recovery can be used to minimise heating energy consumption and hence the environmental impact.

For the spring and autumn seasons, the building could be cooled with natural ventilation using appropriate volumes of outside air. For the summer, the system may return to mechanical ventilation if mechanical cooling is available; if not, it would remain on natural ventilation during occupation, perhaps using mechanical ventilation for night-time cooling.

Problems can be caused with opening windows if the occupants are not clearly informed as to when the system changes over from mechanical to natural ventilation, but there are psychological advantages in allowing occupants control over window opening for at least part of the year.

5.3.1 Hollow core systems

Thermal mass in the building can be used to attenuate heat gain. The effectiveness of the mass can be increased by passing the ventilation air through the structure. This may take the form of hollow core construction which increases the area of exposed mass and improves the surface heat transfer co-efficient. Necessarily, the systems usually require mechanical ventilation to overcome the higher pressure drops through the air paths.

6 MECHANICAL COOLING STRATEGIES

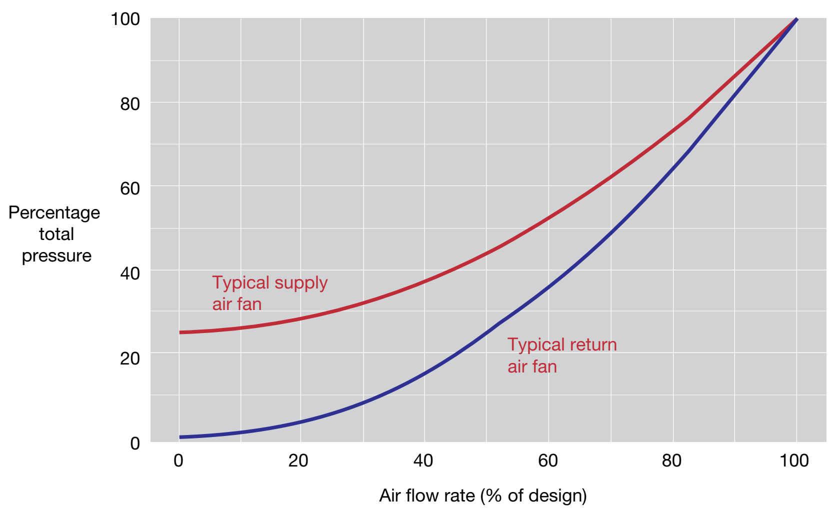
The use of air-conditioning can double the running costs of the building and considerably increase the environmental impact in terms of associated CO_2 emissions (see ECON 19).

Despite this, for applications where tight environmental control is required, mechanical cooling systems have to be considered. However, an energy-efficient approach can also be taken with these systems.

Fan energy used for cooling distribution is the major energy component in conventional centralised air-conditioning and comfort cooling systems. This can be reduced by the following:

- design of the air distribution system to minimise pressure drop, and selection of efficient fans and motors – aim for a target specific fan power of 1 W/l/s
- use of fan speed control to reduce air flow at times of part load; figure 7 illustrates the characteristic of frequency inverter speed control (note – the supply fan power reduces as the cube of the flow rate reduces and tends, not to zero, but to the static pressure sensor setting)
- improve ventilation effectiveness; displacement ventilation may be an option which conditions the immediate space around the occupants rather than the whole space, as is the case with traditional mixing air distribution systems.

Figure 7 Graph of variable air volume fan control characteristics



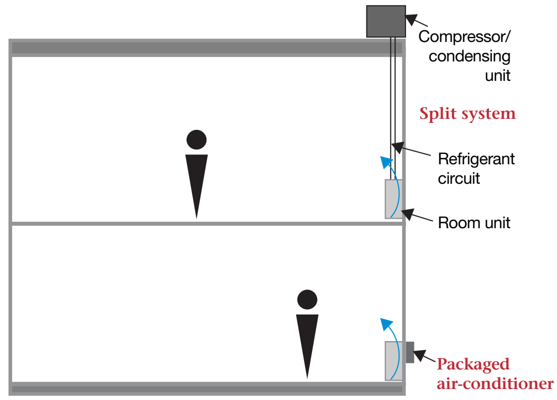


Figure 8 A schematic of unitary systems

The amount of energy used by chillers in office buildings is generally not large in comparison to fan energy in all air systems. The energy use of the cooling systems can be significantly reduced by using water, for example, instead of air as the means of transporting cooling around the building. The transport energy for conveying 1 kWh of cooling around the building in air is about 50 times greater when compared to water, based on typical design parameters.

6.1 COOLING SYSTEMS

There are three generic types of air-conditioning systems.

Unitary systems

Sometimes referred to as 'local' systems, they are characterised by having all their environmental functions contained in a single room unit, eg fan, heating coil, cooling coil and compressor. They are commonly used to serve a single zone or small proportion of a building (see figure 8). 'Split systems' separate the room units, with their fan and heating/cooling coils, from the compressor and condensing units. The latter noisy components can then be placed outside the building.

MECHANICAL COOLING STRATEGIES

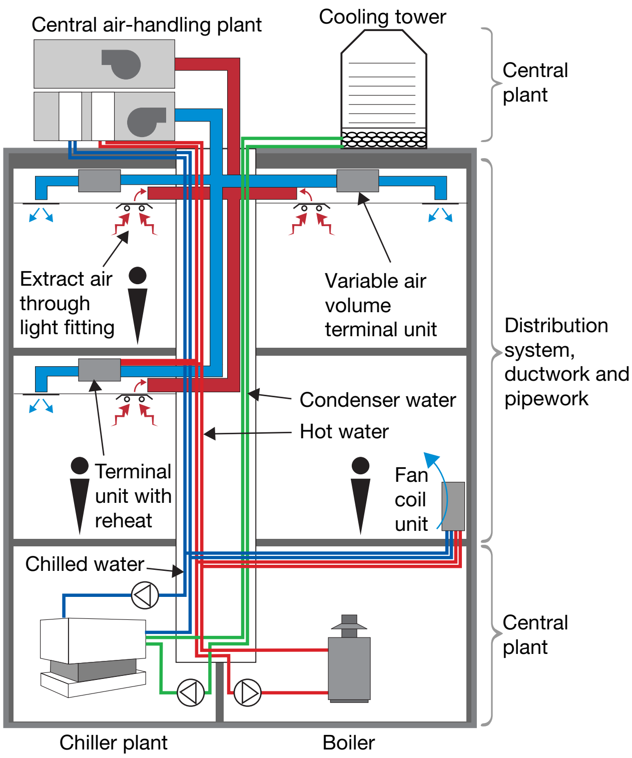


Figure 9 Schematic of a composite centralised system

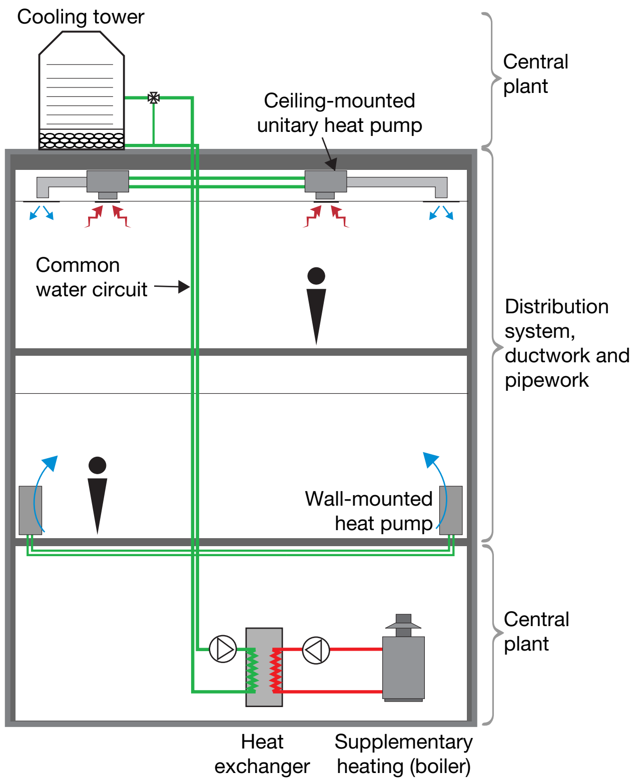


Figure 10 Schematic of a part-centralised system

Centralised systems

Cooling is typically generated by large central chillers which may be water cooled (with a cooling tower) or cooled by outside air; ventilation is provided from a central air-handling plant. This plant is normally located in central plant rooms but may be roof mounted (see figure 9).

Heating and cooling is distributed to the occupied spaces by air or water circuits with the final control of space conditions taken by the terminal units, eg variable air volume boxes, fan coil units, induction units, etc.

Whenever air is distributed around the building from a central location, advantage may be taken of cool outside air to provide 'free cooling', ie cooling achieved without running chiller plant. The cost of increased duct sizes and fan energy needs to be taken into account when designing for this facility.

Part-centralised systems

Typically, these consist of a number of unitary heat pumps connected by a common water circuit, often known by the trade name Versatemp (see figure 10).

Each heat pump is basically a refrigeration machine which draws heat from, or rejects heat to, the water circuit and delivers this heat or 'coolth' to the space. Hence, heat can be recovered from spaces requiring cooling and delivered to spaces requiring heating.

Generally, a central boiler plant provides supplementary heat when all the units are extracting heat from the water circuit in winter. A central cooling tower is used for heat rejection for peak summer operation when all units are rejecting heat to the water circuit. Central air-handling plant (not shown in figure 10) generally provides the ventilation air needs.

MECHANICAL COOLING STRATEGIES

6.1.1 Conventional cooling systems

There are a number of different systems for delivering cooling to the occupied space. These systems depend upon the use of mechanical cooling plant, which is generally centralised. The systems generally use electrical energy for cooling the building, some of which may be supplemented by free cooling. The designer should consider the energy used by the generation and distribution of cooling and the environmental impact of the refrigerants used in those systems.

Variable air volume

A variable air volume (VAV) system is an example of a centralised air-conditioning arrangement. It generates heating and cooling with central plant and delivers conditioned air around the building through the air distribution system. The system controls the amount of cooling to the space by varying the quantity of air delivered in accordance with changes in cooling load in the space. Heating may be either by heating coils in the air supply ductwork or with a separate perimeter heating system.

The VAV terminal boxes regulate the air flow in accordance with the space cooling load. The fan volume is controlled by sensing the resulting change in system pressure. This results in significant savings in fan energy when compared to constant volume systems. The system gives good multi-zone environmental control, but the complexity of the system makes it an expensive solution. Refer to checklist 6 for more details.

Two-pipe or four-pipe fan coil system

The most common form of fan coil system is the four-pipe arrangement, which consists of units either in or near each room, each containing a fan and a heating and a cooling coil. Each coil has a flow and return pipe, hence the term 'four-pipe'. The unit's fan blows room air over the coils.

The fan coil system uses water for the main distribution of heating and cooling around the building. A primary air plant is normally used to deliver ventilation air, which can be dehumidified. By using water as the main medium for distribution, the amount of ductwork is significantly reduced and, as a consequence, so is the space requirement for air-handling plants, risers and false ceiling or raised floor voids.

Even though modern fans are fairly quiet, noise from the units still needs to be borne in mind. The output of the units is often controlled by regulating the flow rates of the chilled or heated water, or by the use of dampers to divert the air flow within the unit with the fan running at constant speed.

As a safety measure in case moisture condenses on the cooling coil, a condensate drainage system is generally provided. Routing this out of the building may prove awkward and has a capital cost.

Variable refrigerant flow (VRF)

Sometimes referred to by a tradename VRV, this is an example of a unitary system which is essentially a split system (see unitary systems, section 6.1) with a roof-mounted condensing unit which may serve a number of room units. Typically the units can operate as either heat pumps or comfort cooling devices.

Distribution of heating or cooling is achieved with refrigerant circuits through which the flow is varied rather than turned on and off as is commonly the case with split units. The refrigeration pipework is considerably smaller than air ducts or water pipes for the same heating or cooling capacity, which simplifies distribution. However, there are other considerations which using refrigerant as a distribution medium imposes – distance from the room unit to the condensing unit and vertical separation must not be excessive to ensure oil return to the compressor. Consideration needs to be given to refrigerant safety aspects in the event of leakage into the space.

6.1.2 Alternative cooling systems

There are now a number of alternative ways of getting cooling into the space. These include such systems as displacement ventilation and static cooling, the latter relying on radiation and natural convection for heat transfer rather than fan power. These are discussed below and in checklists 7 and 8 respectively.

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Displacement ventilation system
Air is supplied at low level to the room at a temperature which is slightly cooler than that of the ambient temperature in the occupied zone and at a very low velocity. The cool air flows across the floor until it encounters heat sources. It then rises past the heat source, picking up its heat and pollutants. The air collects at ceiling level and is extracted through an opening at high level; see figure 11 and checklist 7 for more details. These types of system create temperature stratification in the space which leads to higher air temperatures near the ceiling. For the thermal comfort of the occupants, the temperature difference between the head and feet levels should not be too great (refer to checklist 7). These systems offer good ventilation effectiveness with a good quality environment, pollutants being carried up by the airstream and extracted, instead of merely being diluted.

Chilled ceilings and chilled beams
Static cooling systems use water as the main medium for the distribution of cooling around the building. Unlike systems which rely on fans to distribute the cooling through the space from the room terminal, there will be considerable savings in fan energy. There are two principal forms of static cooling; chilled ceilings and chilled beams, with the following characteristics.

- With chilled ceilings, chilled water is passed through piping which is attached to the back of metal ceiling panels. Alternatively, the chilled water pipes could be embedded in pre-cast concrete ceiling slabs. Cooling is via radiation and convection. The radiation effect allows the thermal comfort of the occupants to be attained at higher room air temperatures than with air systems (see figure 11).
- With static chilled beams, the room air is induced over finned chilled water pipes using natural buoyancy effects (see figure 11).
- Active chilled beams also supply air via the beam from an air-handling unit; hence the total cooling effect is increased.

These ceiling-mounted systems need to be carefully integrated into the ceiling design along with the lighting and partitioning layout, etc.

Static chilled ceilings and chilled beams should not be used in spaces with very high latent gains, as this could result in condensation problems. They also can not deal with very high cooling loads, such as computer equipment rooms.

Night cooling
An established technique, night cooling removes heat which has accumulated in the building fabric during the day by passing the cool night air through the building. The building fabric is cooled and its ability to absorb heat is increased; thus the temperature increase during the following day is limited. Ventilation may be natural or fan-assisted.

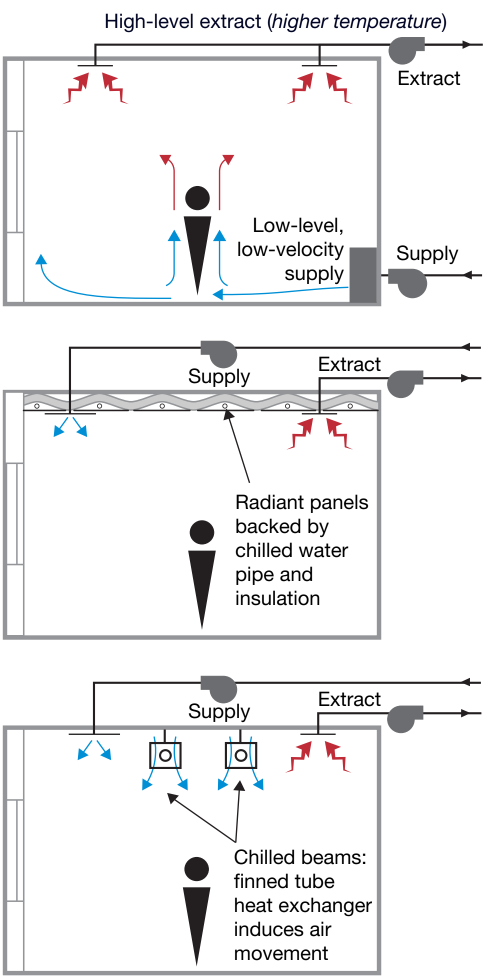

Figure 11 Alternative space-cooling systems (displacement and chilled ceiling/beam)

Displacement ventilation – does not cool the entire space, only areas where there is heat gain

Chilled ceiling (50% radiant, 50% convective) – primary air supply usually required for ventilation and dehumidification

Static chilled beams (20% radiant, 80% convective) – separate primary air supply normally used for ventilation and humidity control

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For the full benefit of night cooling to be achieved, control strategies should be employed which ensure sufficient and not surplus cooling (which might trigger heating at the start of the following day). To be effective, care should be taken in choosing set points which initiate night cooling. Measuring the zone dry-bulb temperature does not in itself indicate the amount of 'coolth' stored in the building fabric; it would be prudent to monitor the air temperature and slab temperature of each zone and also the outside air temperature.

Energy consumption for mechanical cooling and ventilation is reduced which leads to cost savings.

6.2 COOLING PLANT FOR CENTRALISED SYSTEMS

Mechanical cooling of buildings will generally use a refrigeration machine of some description. The vapour compression cycle uses refrigerants which have considerable environmental impact in terms of global warming effects (GWP) and ozone depletion (ODP) if they are released to the atmosphere:

- CFCs – high GWP and high ODP; production phased out in 1995
- HCFCs – high GWP, low ODP; production will be progressively cut to a total phase-out in 2015
- HFCs – substitute for HCFCs; they have zero ODP but still high GWP.

For more details see BRE Information Paper 16/95 'The safety and environmental requirements of new refrigerants'.

Alternative refrigerants can be used, such as propane, isobutane and ammonia, etc, however their application is limited by other considerations.

Absorption machines use a chemical process to produce a cooling effect, but have lower efficiencies than vapour compression machines. However, where waste heat is available (eg from combined heat and power (CHP)), then absorption refrigeration systems could be considered as an energy-efficient alternative. Also, as they use mainly thermal energy rather than electricity, their CO_2 emissions may be lower.

6.2.1 Conventional cooling plant

Distribution systems such as VAV, fan coils, displacement ventilation and chilled beams and ceilings will normally be served by chilled water generated from conventional electric motor-driven vapour compression machines.

Conventional cooling plant uses vapour compression chillers which utilise HCFCs or HFCs as refrigerants. Although these refrigerants are relatively benign when compared to CFCs in terms of their ozone-depleting potential, they still have an appreciable global warming effect if released into the atmosphere, and are a thousand times more potent than CO_2. Appropriate safeguards should therefore be taken to prevent leakage, such as installation and regular plant maintenance being carried out by technicians with suitable certification from the Institute of Refrigeration.

Refrigeration machines

Systems using mechanical cooling will commonly use a refrigeration machine which operates with a vapour compression cycle.

A vapour compression machine is described by its compressor type:

- rotaries and scrolls – small unitary and packaged systems typically up to 100 kW of cooling
- reciprocating machines – having cooling capacities typically up to 1000 kW
- screw machines – typically 500 kW to 1000 kW
- centrifugal machines – for cooling capacities in excess of 500 kW.

High chiller efficiencies can be aimed for by reducing the difference between the chilled water and condensing temperatures, good control on part load, speed control of the compressor and resetting of the condensing temperature when possible, etc.

Conventional vapour compression plants can be operated in an efficient manner to improve part-load performance (at which chillers will operate for the majority of the time). Compressor speed control and scheduling of the condenser water temperature in conjunction with an electronic expansion valve will improve the co-efficient of performance (CoP) of the machines on part-load. It is important that any drive speed arrangements have the approval of the manufacturers to avoid potential problems with loss of lubrication efficiency and creation of electrical harmonics which may damage motor winding insulation, particularly on hermetic machines.

6.2.2 Alternative low-energy cooling plant

Energy-efficient alternatives to conventional refrigeration machines include the use of ground water, evaporative cooling, earth to water heat exchangers and absorption machines coupled with CHP.

Ground water cooling

A naturally available technique which can be used to provide summertime cooling is ground water cooling, which exploits the nearly constant temperature of water obtainable from underground wells or reservoirs.

During the summer, low temperature water (typically 8-10°C in the UK) is extracted from the well and pumped to the surface. There it must be passed through a heat exchanger to separate ground water from system water, otherwise corrosion may occur and bacterial slime from the well may foul the system, thereby decreasing efficiency.

This system water can then cool the ventilation air which is supplied to the building. Alternatively, the system water may pass through the coils fitted in chilled ceilings, although flow temperature control may be necessary to guard against condensation risk. Having picked up heat from the system water, return ground water is discharged from the heat exchanger to a separate 'soakaway' well at an increased temperature.

Only certain sites have suitable ground water sources, hence this technique is restricted by site features. Temperature stability is enhanced with greater depth, but site and substrata characteristics may limit feasible well depths which vary from 10-200 m. Furthermore, at least two wells are required (extract and soakaway) and these must be separated by a horizontal distance of at least 100-150 m. Hence, the site must have sufficient open ground for these and any inspection wells, all of which are expensive to excavate. As water is drawn from a subterraneous reservoir, icing (and the consequent need for defrosting) is not a pertinent factor.

Maintenance may present some difficulties and hazards (eg underground pumps) but most of the plant is at surface level. Licences may be required when exploiting reservoirs and other legal requirements must be met.

Earth to air or water heat exchangers

If the earth temperature is cool enough, it is possible to use it for cooling a building. Earth coupling may be direct, where large surfaces are in contact with the ground, but this has inherent limitations in both cooling capacity and control.

As an alternative, air or water may be channelled underground and cooled in subterranean heat exchangers before being delivered to the building. This established method is termed indirect ground coupling.

Cooled soil can 'flatten' the periodic heat waves when the ambient air temperature rises for several days above the normal level for the season. The time lag between peak ambient air temperature and peak soil temperature can be as large as six months, and this enables greater cooling in summer as the annual soil temperature peak does not coincide with the ambient peak.

Tubes should be placed as deep as is economically viable to give cooling source temperatures as low and as stable as possible. Excavation is costly, especially if the substrata is 'difficult' (eg granite) although, in temperate regions, a depth of 2-3 m may be sufficient for cooling. Heat transfer depends upon soil type and moisture content, and only some sites are suitable.

Cleaning and maintaining a subterranean heat exchanger might also be difficult and expensive. In particular, condensation, a potential breeding ground for microbiological contaminants, may

MECHANICAL COOLING STRATEGIES

form on the air side of the air-ground exchanger coils. This may be difficult to remove and is a potential health issue.

Evaporative cooling

Indirect evaporative cooling is preferred to direct, as it avoids the spraying of water directly into the air stream and possible microbiological contamination of the supply air. Some direct systems avoid this problem by spraying the exhaust air stream prior to an air heat recovery device so that the latent heat transfer from the exhaust air provides sensible cooling to the supply air path without risk of cross-contamination.

Cooling towers can be used as indirect evaporative coolers, as an alternative to using refrigeration machines for part of the year. The cooling tower water circuit is routed to a heat exchanger in the chilled water circuit, instead of to the condensers. Towers can be natural or forced draught and in a variety of configurations to enhance the latent heat transfer between the cooling water and external air. Precautions are needed with open towers to filter out debris and microbiological contamination which might foul the heat exchanger.

The success of this system is closely linked to the ambient wet bulb temperature. This is less than 16ºC for 50% of the time in the UK, which is sufficient to obtain a useful flow temperature (particularly for, say, chilled ceiling applications). At peak conditions the ambient wet bulb may be as high as 20ºC, so the cooling water flow temperature would be high (of the order of 23ºC). Under these conditions, the system would revert to the conventional chiller, with the condenser water flowing through the cooling tower.

Absorption chillers

The technology for absorption chillers was established in the 1800s but has often been neglected. It has seen a recent resurgence in conjunction with CHP plants. To run the refrigeration cycle the only major requirement is heat, which can be supplied in various forms according to the power plant. One potential heat source is CHP, which comprises gas engines coupled to electricity generators. The absorption chillers make use of the not-insignificant heat from the engine cooling system which would otherwise go to waste outside the heating season.

The absorption refrigeration cycle uses a binary mixture of two miscible substances – the refrigerant and the sorbent. The generator provides heat (which may be from the exhaust gases or jacket water of the CHP) to the liquid mixture which then separates into its two components, releasing the refrigerant vapour. The sorbent drains to the absorber. Pressure pushes the refrigerant vapour to the condenser where it is cooled (transferring heat to the condenser water) and condensed back to liquid refrigerant form. This then flows to the evaporator. The water to be chilled flows over the outside of the evaporator, transferring its heat to the liquid refrigerant, causing it to vaporise. The refrigerant vapour is drawn to the absorber where it meets the sprayed sorbent, is absorbed back into the solution and dissipates more heat to the condenser water. The solution is pumped back to the generator to begin the cycle once more.

Although the heat energy available will depend on the flow and temperature rise of the hot water transferring heat to the generator, the supply and return temperatures themselves have a significant influence on the size of the absorption chiller and higher temperatures allow greater refrigeration. Lower water temperatures (up to 130ºC, eg from jacket water) lend themselves to single-stage cycles (CoP 0.6-0.75), while double-stage systems are used for higher equivalent saturation water temperatures. Double-stage systems may be steam fired (CoP 1.1-1.2) or hot (exhaust) gas driven (CoP 1.05-1.15). Low hot water temperatures require the use of very large chillers.

Medium to large water chillers (30-6000 kW) use a mixture of lithium bromide (refrigerant) and water (sorbent). Another common mixture is of water (refrigerant) and ammonia (sorbent). The H_2O/NH_3 mixture does not crystallise at operational conditions but requires more complex distillation apparatus. Other mixtures are used.

To enable the refrigerant to boil at low temperatures the chillers work under vacuum. This necessity can be troublesome and vacuum pumps are normally fitted to all units to maintain the required conditions. Mechanical components are the absorber pump, generator pump, solution pump, purge (vacuum) pump and, for gas-fired units, the burner. Such chillers have been known to operate almost continuously for over a decade with little day-to-day maintenance required.

The analysis of schemes coupled to CHP can be complex due to the inter-relationships between the site requirements, energy prices and the CHP plant type. Generally, it is worth investigating CHP systems if a plant is to be run for more than 4500 hours per year. Thus, if the absorption chiller can make use of heat from the CHP plant, the operating hours per year will more closely approach this figure than if it was used for heating alone. If a CHP plant is to be considered, data on electrical and heating requirements throughout the year is vital. Careful design installations can give total system efficiencies of up to 90%. As a guide, approximately 27% of the fuel input is converted to useful electrical power and 55% to useful heat. The nature of the equipment demands a high maintenance provision, but payback is generally within five years.

APPENDIX – CHECKLISTS

NOTES ON THE USE OF THE CHECKLISTS

1 The checklist presents information on aspects of the HVAC services and environmental control in a standardised way.

CHECKLIST NUMBER AND TITLE	
Heading	
Subheading	General information about the system, its characteristics and performance
	System characteristics which should be considered with caution as they may cause problems

2 To assist in the comparison between system types a notional building has been assumed for the calculation of energy consumption and costs. The details of the building are as follows.

- A six-storey rectangular building has a length of 46 m, a width of 18 m and a floor-to-ceiling height of 3 m; the building is on an east-west axis.
- Total treated floor area of approximately 5000 m^2.
- Lighting load assumed to be 15 W/m^2. Small power assumed to be 15 W/m^2.
- Occupancy of one person per 10 m^2, the latent and sensible occupancy loads were taken for light work with the internal temperature maintained between 22ºC and 24ºC.
- Glazing has a U-value of 3.3 W/m^{2}K and covers 50% of each façade seen from the outside.
- Solar gain data, as well as outdoor air temperature and enthalpy were taken for Kew, London.
- Occupancy was assumed to be between the hours of 8 am and 6 pm, Monday to Friday.
- Fresh air was supplied at a minimum of 8 l/s/person.
- Where appropriate, the boiler seasonal efficiency was taken to be 0.75, hot and chilled water distribution efficiencies both 0.90.
- Fan efficiency was taken as 0.75, the combined fan motor and drive efficiency was 0.95.

3 The building has been considered at various heat gains appropriate to the system capacity, ie displacement ventilation @ 40 W/m^2, chilled ceilings @ 70 W/m^2, fan coil system @ 95 W/m^2.

4 The energy and cost indicators given in the checklists (gas 0.81 p/kWh, electricity 5.1 p/kWh) have been derived for general office applications for first quarter 1998, and should serve only as a rough guide in the option appraisal. If building specific data are available these should be used in preference.

5 Values presented for systems with free cooling are based on the assumption that such systems use outside air and not water.

6 No wintertime humidification has been included in the energy and cost estimates.

7 Equivalent hours at full load are applied to installed loads for energy calculations.

8 Assumed CO_2 conversions – electricity 0.46 kg/kWh, gas 0.19 kg/kWh.

APPENDIX – CHECKLISTS

CHECKLIST 1 – BUILDING THERMAL CHARACTERISTICS

Shape (1.1)	
	Narrow plan will allow natural ventilation: ■ single-sided ventilation, for building widths up to twice the floor-to-ceiling height ■ cross-ventilation, for building widths up to five times the floor-to-ceiling height.
	Deep plan (greater than 15 m) will require more sophisticated forms of natural ventilation or mechanical ventilation and may require application of mechanical cooling systems.
Windows (1.2)	
	Limitation of the window area is critical to the thermal performance of the building.
	A balance must be struck between the avoidance of excessive solar gain and heat loss and the need for daylight.
	Glare and direct radiation will need to be controlled by some form of shading (see below).
	Large window areas will cause large heat loss and large heat gain and require complex HVAC plant.
	The design of the window is critical to the performance of naturally ventilated designs in terms of controllability of wintertime minimum fresh air and summertime maximum air movement, for instance by using trickle vents.
Mass (1.3, 1.4)	
	Mass in a structure has the potential to attenuate heat gain but may not necessarily affect the thermal response of a space. Its location is important – the first 100 mm of fabric surface facing into the room is the most influential.
	For mass to be effectual in attenuating heat gain for prolonged periods of warm weather, it must be coupled with night cooling in climates with a peak day diurnal range of at least 5ºC.
Insulation (1.5,1.6)	
	Insulation is good for winter and summer operation, reducing peak heating and cooling demands.
	It improves perimeter comfort conditions, reducing the zones of discomfort near external walls.
	Location of insulation is important; it influences both the thermal response time of the building and the risk of interstitial condensation.
Shading (1.2)	
	Shading devices can reduce the direct solar gain through glazing, which on some naturally ventilated buildings becomes essential to delivering comfort conditions in the space.
	Best devices are external but these are expensive – options include deep reveals, over-hangs, fixed or motorised louvres.
	Mid-pane blinds is the next most effective option.
	Internal blinds are very often required for local glare control. Shading may also be provided for roofs or other fabric elements.
Airtightness (1.7, 1.8)	
	The building should be made as airtight as possible and be coupled with a design which supplies the ventilation air in a controlled way – incidental air movement should be avoided.
	An airtightness standard of 5 m^3/h per m^2 of facade at 25 Pa pressure difference is good.
	Pay particular attention to the detailing and construction of joints in the building fabric – at doors and windows, wall to ceiling joints and cladding joints.
References	
	1.1 CIBSE. AM10. Natural ventilation in non-domestic buildings (1997)
	1.2 CIBSE. AM2. Window design (1987)
	1.3 BRECSU. GIR 31. Avoiding or minimising the use of air-conditioning (1995)
	1.4 BSRIA. Dynamic energy storage in the building fabric (1994)
	1.5 BRE. BR262. Thermal insulation: avoiding risks (1994)
	1.6 EMAP Architecture. SPECIFICATION 94: Thermal Design
	1.7 BRE. Airtightness of UK buildings and future possibilities (1992)
	1.8 BRECSU. GIR 30. A performance specification for the energy efficient office of the future (1995)

APPENDIX – CHECKLISTS

CHECKLIST 2 – NATURAL VENTILATION	
Techniques (2.1)	
General	Heat gain in the space should be less than 40 W/m² for these techniques to meet comfort criteria.
Single-sided	Effective for building widths up to twice the floor-to-ceiling height.
	Design of windows are critical for minimum fresh air in winter (trickle ventilation to prevent cold draughts).
	Horizontal pivoted and vertical sash windows have good ventilation capacity, air entering at low level and leaving under buoyancy effects at high level. Side or vertical pivoted windows are less effective.
Cross flow	Effective for building widths up to five times the floor-to-ceiling height, spatial layout restrictions in order to maintain crossflow of ventilation air.
Stack	Effective for up to five times the floor-to-ceiling height, measured between the air inlet and the stack.
	Very low pressure differentials developed <10 Pa, ducts and stacks must be generous to minimise pressure loss.
Wind tower	More pressure differential to work with, but wind pressure less predictable. Hence control is complex.
Environment (2.2)	
General	Occupants have a broad tolerance to naturally ventilated buildings, they understand them, they have individual control (openable windows) and generally accept the peak summertime periods when control is lost on temperature and RH.
	Buildings with good thermal characteristics and low susceptibility to solar gain can restrict summertime space temperatures above 28ºC to less than 1% of occupied hours using natural ventilation.
	Air quality can be a problem in urban sites as filtration is difficult.
	External noise transmission needs to be considered where simple opening windows and vents are used.
Dry bulb temperature	Control will be lost in summer, although a 2-3ºC depression of daytime peaks can be achieved with night cooling.
Humidity	No control.
Air movement	Occupants near the perimeter will have control for single-sided ventilation.
	Stack ventilation can achieve sufficient air movement even during still summer peak conditions.
Odour level control	Good dilution rates are achievable at the perimeter. Wintertime ventilation needs to be considered with care. Trickle ventilation is an option but avoid the creation of cold drafts by locating the vents at high level or preheating the air.
Air cleanliness	No control – can be problematic for buildings adjacent to busy roads and industrial sites which create dust and dirt, or rural sites which may suffer from high pollen levels.
	The pressure generated by stack ventilation is too low for conventional air filtration.
Space requirements	
General	For simple systems no plant space is required for ventilation or cooling systems.
	Stacks may occupy gross floor area, but the use of stairwells or atriums to generate stack force will minimise their impact on the net to gross ratio.

APPENDIX – CHECKLISTS

CHECKLIST 2 – NATURAL VENTILATION *(continued)*	
Energy (2.1, 2.3, 2.4)	
General	The naturally ventilated building has simple HVAC systems and as a consequence has a low energy consumption. There is no fan energy – air movement is achieved through well-designed opening windows or more sophisticated ventilation stacks and flues which make use of wind and buoyancy effects. Simplest of systems yields the lowest energy consumption (best practice – office buildings): ■ space heating 72 kWh/m² ■ fans and pumps 3 kWh/m² **HVAC-related CO_2 emissions:** ■ space heating 13.7 kg/m² ■ fans and pumps 1.4 kg/m² **HVAC total 15.1 kg/m²**
Costs (2.5, 2.6, 2.7) (based on quarter 1 1997 prices)	
Capital	The capital cost of the mechanical services will be low in such buildings but considerably more may need to be spent on the building fabric to achieve good thermal characteristics. Building capital costs can be in excess of £1000/m², see case studies in AM10. Mechanical services capital costs will be a small proportion of this, typically £35-£40/m². If a BMS is used add £20/m². See client's Guide GPG 290 for more actual costs.
Maintenance	HVAC annual maintenance costs £0.8-£1.4/m². If motorised openings are used £3-£5/m².
Energy	HVAC annual energy costs for the notional building are £0.78/m².
References	
	2.1 CIBSE. AM10. Natural ventilation in non-domestic buildings (1997) 2.2 BRECSU. GIR 31. Avoiding or minimising the use of air-conditioning (1995) 2.3 BRECSU. GIR 30. A performance specification for the Energy Efficient Office of the Future (1995) 2.4 BRECSU. ECON 19. Energy use in offices (2000) 2.5 GTES. Building Cost Survey – commercial offices (urban environment) (Sept 1995) 2.6 GTES. Building Cost Survey – commercial offices (non-urban environment) (Nov 1995) 2.7 DTI. Energy Trends (Dec 1997)

APPENDIX – CHECKLISTS

CHECKLIST 3 – MECHANICAL VENTILATION	
Techniques	
Simple extract	Low capital and energy cost but will need to be run in mixed-mode, ie natural ventilation to give high air flow rates for summertime operation to obtain adequate air movement for comfort. Make-up air path needs to be designed to minimise draughts and dust/pollution ingress.
Supply and extract	Ducted distribution will permit ventilation heat recovery (see checklist 4), filtration and humidification. Speed control on the system fans will minimise the fan energy and allow turndown to minimum fresh air during wintertime. Mechanical ventilation and thermal mass can be combined for greater effectiveness in the form of ventilated voids (see 'Hollow core', below). More building space is required to accommodate air-handling plant and distribution ductwork. To avoid the energy penalty from high air flow rates which may be required in summer, the system will need to be run in mixed-mode; ie mechanical ventilation for winter, natural ventilation for summer.
Hollow core	The usefulness of thermal mass is governed by the surface area which is available for heat exchange, the heat transfer co-efficient between air and mass and the contact time. Moving air through the structure itself, instead of just over it, has the potential to improve all three factors and thus improve the effectiveness of available mass. The system can be used throughout the year for thermal storage: ■ in summer, with night-time ventilation of the mass, cooling is stored, and used the next day to cool the supply air before passing it to the occupied space ■ in winter, waste heat from internal gains or electric heating can be stored in the fabric to be re-used when the building has a heating demand.
Environment (3.1)	
General	Improved environmental quality when compared with naturally ventilated solutions. More predictable performance from night cooling under all conditions.
Dry bulb temperature	Hollow core systems have more mass in play and, therefore, have the potential to perform better than simple mechanical ventilation systems.
Humidity	Normally no control but the ducted system can be used to supply winter humidification to the space.
Air movement	Needs to be applied on a mixed-mode basis – mechanical ventilation for winter and night cooling, natural ventilation for summertime.
Odour level control	Good, year-round performance with wintertime minimum fresh air rates guaranteed. Fresh air rates set according to odour source.
Air cleanliness	Good filtration standard achievable – the price for higher air cleanliness is capital cost and increased fan energy.
Space requirements	
General	Space requirement for air-handling units and risers approximately 3-5% of treated area. For simple extract systems, space requirement for air-handling plant is small – approx 1%. For buildings with higher ventilation loads, eg retail, plant will be larger and space requirements greater.

APPENDIX – CHECKLISTS

CHECKLIST 3 – MECHANICAL VENTILATION *(continued)*	
Energy (3.2)	
General	For the notional building* mechanical ventilation supply and extract systems with exhaust air heat recovery: ■ space heating 60 kWh/m^2 (system using ventilation heat recovery) ■ fans and pumps 8 kWh/m^2 *(*see note 2 on page 24)*
	Fan energy can be significant, particularly if control of the operational hours is sloppy. There are many examples where the design intent has been right but has been ruined because fan operation has been poorly controlled or there has been insufficient attention to the detail of the air distribution pressure drops. Fan energy can be several times the figure given above.
	HVAC-related CO_2 emissions: ■ space heating 11.4 kg/m^2 ■ fans and pumps 3.7 kg/m^2 **HVAC total 15.1 kg/m^2**
Fan hours run	Typical fan hours run at full load are given below for various volume flow rates and control regimes. *Hours run at full load* 100% flow 2250 hours Minimum fresh air 550 hours Night-time run hours Night cooling (exposed soffit) @ 4 ach 850-1400 hours @ 8 ach 775-925 hours Night cooling (hollow core slab) @ 4 ach 600-1300 hours @ 8 ach 650-775 hours
Costs (3.3, 3.4)	
Capital	Mechanical systems costs between £40/m^2 and £80/m^2.
Maintenance	Supply and extract system maintenance costs between £1.80/m^2 and £2.40/m^2 per year.
Energy	HVAC energy costs for the notional building are £0.90/m^2/year.
References	
	3.1 BRECSU. GIR 31. Avoiding or minimising the use of air-conditioning (1995)
	3.2 BSRIA. Dynamic energy storage in the building fabric (1994)
	3.3 DTI. Energy Trends (Dec 1997)
	3.4 SPONS. Mechanical and Electrical Services Price Book (1998)

APPENDIX – CHECKLISTS

CHECKLIST 4 – MECHANICAL VENTILATION HEAT RECOVERY	
Techniques (4.1)	
Thermal wheel	Available for air flow rates up to 30 m^3/s. Effectiveness ranges between 70% and 80% for sensible heat exchange and equal mass flows of supply and exhaust air. Typical pressure drops 100-200 Pa (2.5 m/s face velocity).
Plate heat exchangers	Modular air-handling units have plate heat exchangers available up to 5 m^3/s supply volume. The effectiveness of the heat exchanger will vary with air mass flows and velocities, for equal mass flows the effectiveness will range between 60% and 70%.
Run around coils	For a supply volume which is twice that of the extract, the range of effectiveness increases to between 75% to 85%. The pressure drop through the heat exchanger will be of the order of 250 Pa. The run around coil transfers heat through a water circuit which adds flexibility since the heat exchangers need not be adjacent. The effectiveness of the coils is between 60% and 65%. Many applications will require the use of anti-freeze solution in the heat recovery circuit; this reduces the heat transfer effectiveness to something of the order of 50%. Pump power consumption reduces overall energy efficiency. The coils can be sized to suit a low pressure drop requirement; typically 100 Pa to 150 Pa is achievable.
Energy (4.2)	
General	The proportion of ventilation heating energy recoverable with the use of air to air heat exchangers is indicated in figure 6 on page 14 (for a supply temperature of 17ºC and an extract temperature of 23ºC (site: London)).
Costs	
Capital savings	Account should be taken of any reduced size of boilers, pumps and pipework because of the lower heat demand. Reduced size of cooling plant – chillers, pumps chilled water pipework and coils. Smaller gas main, smaller electrical supply.
Capital costs	Air to air heat recovery device. Larger fans for higher pressure drops and additional ductwork and filtration equipment. Heat recovery controls.
Savings – energy costs	Heating energy recovered. Cooling energy recovered.
Additional energy costs	Fan energy because of higher pressure drops. Maintenance costs of the heat recovery device and filtration system. Parasitic motive power consumption (thermal wheel/run around coils).
References	
	4.1 ASHRAE. Handbook – HVAC systems and equipment **4.2** CADDET. Analyses series No. 15. Energy efficient HVAC systems in office buildings (1995)

APPENDIX – CHECKLISTS

CHECKLIST 5 – MIXED-MODE SYSTEMS	
Techniques	
Changeover method	Different systems are used during different times of the year: ■ winter mechanical ventilation – minimum fresh air with exhaust air heat recovery, building sealed ■ spring and autumn natural ventilation to allow large volumes of outside air into the building for free cooling ■ summer, return to mechanical ventilation if mechanical cooling available, if not, remain on natural ventilation perhaps using mechanical ventilation for night-time cooling.
	This type of operation may confuse the building occupants unless it is clearly explained what they should be doing at particular times of the year in terms of opening and closing windows.
Zoned systems	Natural ventilation on the perimeter and mechanical ventilation in the core where mechanical cooling may also be used. This approach may also be adopted where there are particular areas with high heat gain or high ventilation rates.
Space requirements	
General	Space requirements will be the same as for mechanical ventilation systems handling the same range of air volumes – space requirement for air-handling units and risers approximately 3-5% of treated area.
	For simple extract systems, space requirement for air-handling plant is small – approximately 1% of treated floor area.
Energy	
General	See energy consumption data for mechanical ventilation systems (checklist 4).
Cost	
Capital costs	Mixed-mode systems may have higher capital costs if two systems are specified, eg natural ventilation for the transitional seasons and mechanical cooling for the summer.
	However, judicious choice of systems can reduce system costs, eg mechanical ventilation for wintertime minimum fresh air and natural ventilation at other times (thus avoiding large supply air flow rates, and large air-handling plant and ductwork) to achieve comfort conditions in warm weather.
Energy costs	Mixed-mode offers the security of improved environmental conditions, using mechanical ventilation or mechanical cooling without the need to operate fans and chillers throughout the year.

APPENDIX – CHECKLISTS

CHECKLIST 6 – CONVENTIONAL AIR-CONDITIONING SYSTEMS	
Techniques	
Variable air volume systems	An example of a centralised system capable of dealing with large cooling loads in excess of 100 W/m^2.
	Cooling is distributed by air supply. Duct sizes, and hence capital cost, can be reduced by making use of the diversity which exists in a building, ie the peak cooling load will occur at different times of the day for different orientations.
	Consider fan motor speed control to make use of fan energy savings when turning supply volumes down.
	Instead of limiting turndown to 40% for air supply for fixed geometry outlets, consider variable geometry outlets which permit a greater turndown ratio.
	If there is a wide variation in cooling load within the building, over-cooling of the space or reheat may be the penalty. It might be necessary to provide heating by another system (eg perimeter heating).
Fan coil units	Another example of a centralised system, this time using water as the main means of heating and cooling distribution. Capable of dealing with high cooling loads in excess of 100 W/m^2.
	Four-pipe systems are the norm, but two-pipe changeover systems can be used successfully in buildings with good thermal characteristics; this can reduce system capital costs.
	Good multi-zone control characteristics.
	Maintenance costs may be greater because of the greater number of room units with fans, filters and controls which need attention. This may be more awkward to undertake where access to these components is located within occupied areas.
Unitary heat pumps with closed loop water circuit	A hybrid of centralised and unitary systems – unitary heat pumps are connected by a common water circuit which performs the function of heat source and heat sink.
	Thus, because heat rejected by one heat pump can be used as a heat source by another, the system offers some measure of heat recovery.
	When all the heat pumps are drawing heat from the circuit (eg for preheat) there is a need for some means of supplementary heat, eg gas-fired boiler plant.
	When all the heat pumps are cooling the building and dumping heat to the water circuit there is a need to have a means of heat rejection, eg closed cooling tower.
	Room units are capable of dealing with high heat gain, in excess of 100 W/m^2.
	Maintenance costs may be higher than for centralised air-conditioning systems for the same reasons that affect the fan coil system.
Floor supply (mixing type outlets)	Air supplied to a raised floor void from a central air-handling plant, is delivered to the space at constant volume through diffusers mounted on raised floor tiles. This system must not be confused with displacement ventilation (see checklist 7) – both are low-level supply but there are differences. ■ Floor supply systems using 'swirl' type diffusers create high levels of mixing at the lower levels of the space, while displacement ventilation introduces the supply air in a less turbulent way so that air movement is driven by temperature gradients. ■ Mixed systems are capable of handling loads in excess of 100 W/m^2, whereas with displacement systems the maximum load, for ceiling heights of the order of 3 m, will be about half that.

APPENDIX – CHECKLISTS

CHECKLIST 6 – CONVENTIONAL AIR-CONDITIONING SYSTEMS (*continued*)	
Environment ***(all systems)***	
Dry bulb temperature	High-quality control is possible with modulating air dampers and water valves controlled from conditions in the occupied space.
	For a unitary system using on/off control of the room unit compressors, the quality of control will be coarser.
Humidity	Year-round humidity control can be achieved with systems using a central air-handling plant.
	Humidity control can be costly to operate, particularly with electrical generation of steam. Unitary systems without primary air plant humidification may experience low humidities (ie <30% RH) when fresh air moisture content is low, eg in winter.
Odour level control	Good, year-round control.
	For unitary systems without primary air plant, odour control will be more unpredictable.
Air cleanliness	Central air handling allows any desired standard to be achieved for the supply air; typically for an office this would be of the order of EU6 or EU7.
	Unitary system without a primary air plant will depend on the room unit filter which is normally inferior to those which can be specified for a central air-handling plant.
Air movement	Good air movement is achievable with all systems.
	Floor supply systems will have a zone of discomfort immediately around the outlet.
Space requirements	
General	Generally (all areas expressed as a % of treated floor area): ■ all air systems (VAV, floor supply) require 4-8% and greater floor-to-floor heights may be required to accommodate horizontal ducts ■ air and water systems (fan coils) require 3-6% ■ unitary systems without primary air require 1% ■ unitary systems with primary air require 1.5-2.5%.
	Central plant systems are a great consumer of space, boiler rooms, chiller rooms, and particularly air-handling plantrooms, riser space, ducts in false ceilings and raised floors, etc. Components are typically distributed around a building and access may be required through occupied areas. Heat rejection equipment is typically located on the roof.
Energy	
Variable air volume systems	Fan energy on conventional constant volume systems would be one of the main consumers of electrical energy in modern buildings. Fan energy savings can be made by reducing the volume to match the load. Savings depend on the type of fan control used and the variation in cooling load – least with damper control, most with fan motor speed control.
	As a rough guide the equivalent hours run at full load: ■ VAV supply and extract — 1800 hours (with fixed fresh air) ■ chilled water pumps — 2500 hours ■ heating pumps — 3500 hours ■ condenser water pumps — 1750 hours ■ chiller run hours — 500 hours (free cooling); 1200 hours (with fixed fresh air) ■ heat rejection fans — 1200 hours (with free cooling); 1500 hours (with fixed fresh air)
	The energy consumption for a notional building. For the notional building* with a maximum heat gain of 95 W/m^2: ■ heating — 59 kWh/m^2 ■ chillers — 11 kWh/m^2 ■ fans and pumps — 20 kWh/m^2
	*(*see note 2 on page 24)*

(continued overleaf)

APPENDIX – CHECKLISTS

CHECKLIST 6 – CONVENTIONAL AIR-CONDITIONING SYSTEMS *(continued)*	
Energy *(continued)*	
Variable air volume systems	**HVAC-related CO_2 emissions:** ■ space heating 11.2 kg/m^2 ■ chiller 5.0 kg/m^2 ■ fans and pumps 9.2 kg/m^2 **HVAC total 25.4 kg/m^2** The above example is a well-run (ie well-managed and controlled) system; more typically, from ECON 19: ■ heating 178 kWh/m^2 ■ chillers 31 kWh/m^2 ■ fans and pumps 60 kWh/m^2 ■ humidification 18 kWh/m^2 If turndown is limited, consider the reheat energy which will be required to prevent overcooling of the space. Reconsider the zoning of the air system and condenser heat recovery to minimise reheat energy requirements.
Fan coil units	With the distribution of cooling energy carried mainly in the water circuits, the fan and pump energy will be lower than for an all air system. As a rough guide, a fan coil system for an office building with fixed speed motors will have the following equivalent hours run: ■ primary air fans 3000 hours ■ heating pumps 3500 hours ■ fan coil units 3500 hours ■ chilled water pumps 2500 hours ■ chiller 600 hours ■ cooling tower fans 1500 hours ■ condenser water pumps 2500 hours The energy consumption for a notional building. For the notional building* with a maximum heat gain of 95 W/m^2: ■ heating 59 kWh/m^2 ■ chillers 12 kWh/m^2 ■ fans and pumps 28 kWh/m^2 **HVAC-related CO_2 emissions:** ■ space heating 11.2 kg/m^2 ■ refrigeration 5.5 kg/m^2 ■ fans and pumps 12.9 kg/m^2 **HVAC total 29.6 kg/m^2**
Unitary heat pumps with closed loop water circuit	Unitary heat pumps have the facility to recover heat. The amount of heat energy saved depends on the availability of recovered heat and the demand. However, in modern office buildings these are not always in phase. The heat pumps will need to operate in winter to transfer heat from the water circuit into the spaces. Electrical energy will be expended together with a contribution to the building maximum demand at the time of the highest MD tariff charges. For the notional building* with a maximum room sensible heat gain of 95 W/m^2: ■ supplementary heating 44 kWh/m^2 ■ unitary heat pumps 35 kWh/m^2 ■ fans and pumps 8 kWh/m^2 **HVAC-related CO_2 emissions:** ■ space heating 8.4 kg/m^2 ■ unitary heat pumps 16.1 kg/m^2 ■ fans and pumps 3.7 kg/m^2 **HVAC total 28.2 kg/m^2** *(*see note 2 on page 24)*

APPENDIX – CHECKLISTS

CHECKLIST 6 – CONVENTIONAL AIR-CONDITIONING SYSTEMS *(continued)*	
Costs	
Variable air volume systems	***Capital.*** The capital costs of 'all-air' central air-conditioning systems are usually amongst the highest, mainly due to the costs of the distribution ductwork. Typically, the cost of the HVAC systems are £160-£250/m^2 of treated floor area.
	Maintenance. The HVAC annual maintenance costs will be typically £7.5-£13/m^2 of treated floor area.
	HVAC energy costs. For the notional building, HVAC energy costs are £3/m^2 per year.
Fan coil system	***Capital.*** The capital costs of air and water systems will be lower than those for all-air central air-conditioning systems because of the smaller distribution ductwork. Typically the cost of the HVAC systems are £140-£200/m^2 of treated floor area.
	Maintenance. The HVAC annual maintenance costs will be typically £9-£15/m^2 of treated floor area.
	HVAC energy costs. For the notional building, HVAC energy costs are £2.50/m^2 per year.
Unitary heat pumps	***Capital.*** The capital costs of unitary heat pump systems will not benefit fully from the low-cost features of a unitary system because of the need to have central supplementary heating, heat rejection, and central air-handling plant. Typically, the cost of the HVAC systems are £170-£200/m^2 of treated floor area.
	Maintenance. The HVAC annual maintenance costs will be typically £10-£20/m^2 of treated floor area.
	HVAC energy costs. For the notional building, HVAC energy costs are £2.55/m^2 per year.
References	
	CADDET. Analyses series No. 15. Energy efficient HVAC systems in office buildings (1995)
	DETR. ECON 19. Energy efficiency in offices (2000)
	SPONS. Mechanical and Electrical Services Price Book (1998)
	DTI. Energy Trends (Dec 1997)

APPENDIX – CHECKLISTS

CHECKLIST 7 – DISPLACEMENT VENTILATION	
Techniques (7.1)	
General	The principle of displacement ventilation is based on the concept of an ideal air flow pattern. Instead of total mixing achieved by more commonly adopted air distribution systems the flow is unidirectional, with minimum possible spreading of contaminants. This ideal air flow pattern can be achieved by supplying air to the room at low level at a temperature slightly lower than that of the occupied zone (>18ºC) and removal of hot vitiated air at high level. Supply air enters the occupied space at a low velocity and creates a 'pool' of fresh air which is distributed evenly across the floor. At local heat sources such as people or equipment, the air temperature is raised. The natural buoyancy of the heated air gives rise to plumes which are relied upon to create upward air currents, drawing up the conditioned air, thus removing pollutants and heat to high level. The main reasons for the interest in this system are due to the potential benefits of higher air quality in the occupied zone and the reduced running costs of the system because of the increased ventilation effectiveness. The higher temperature chilled water requirement also offers better refrigeration CoPs. A separate small refrigeration machine can be used for dehumidification.
Environment	
General	The system works better with high temperature differences between supply and exhaust air. As higher extract temperatures may be tolerated where a large floor-to-ceiling height exists, it follows that displacement ventilation functions better with larger floor-to-ceiling height, a variable which determines the maximum cooling load. For displacement ventilation to be effective, the minimum practical floor-to-ceiling height is 3 m, and so the maximum cooling load is of the order of 40 W/m^2. This is limited by the low-level supply temperature, which is usually a minimum of 18ºC.
Dry bulb temperature	Reasonable control throughout the year. Temperature gradients will exist through the occupied space – design to a limit of 3ºC between ankle and head.
Humidity	Year-round humidity control possible, but high supply temperature (>18ºC) may require reheat.
Air movement	Reasonable air movement. However displacement air patterns can be broken up if the building has high infiltration rates or considerable occupant movement, and this will reduce the effectiveness of the system.
Odour level control	Good year-round performance with wintertime minimum fresh air rates guaranteed.
Air cleanliness	Can be arranged to provide a standard range of air filtration.
Space requirements	
General	Space requirement for chillers, heat rejection, air-handling units and risers approximately 4-6% of treated floor area.
Energy	
General	For the notional building* with maximum heat gain of 40 W/m^2 and exhaust air heat recovery: ■ space heating 52 kWh/m^2 ■ fans and pumps 15 kWh/m^2 ■ cooling 5 kWh/m^2 **HVAC-related CO_2 emissions:** ■ heating 9.9 kg/m^2 ■ fans and pumps 6.9 kg/m^2 ■ chillers 2.3 kg/m^2 **HVAC total 19.1 kg/m^2** *(*see note 2 on page 24)*

APPENDIX – CHECKLISTS

CHECKLIST 7 – DISPLACEMENT VENTILATION *(continued)*	
Energy *(continued)*	
Fan hours run	100% flow – 2250 hours run at full load. Wintertime minimum fresh air – 550 hours run at full load. Night cooling (exposed soffit) @ 4 ach – 850-1400 hours run at full load.
Refrigeration hours run	The high supply air temperature of 18ºC will mean that greater use can be made of free cooling compared to a conventional system of say 12ºC supply air. Refrigeration hours run at full load <500 hours.
Ancillary equipment	Cooling tower fans 1-2 kWh/m^2.
Costs	
Capital	Chilled water pumps 2-3 kWh/m^2 (constant volume). Condenser water pumps 2-2.5 kWh/m^2 (constant volume).
Maintenance	HVAC system costs range between £120/m^2 and £140/m^2. HVAC systems maintenance costs range between £6/m^2 and £10/m^2.
Energy	HVAC energy costs for the notional building are £1.44/m^2.
References	
	7.1 BSRIA. Displacement ventilation (1990)

APPENDIX – CHECKLISTS

CHECKLIST 8 – STATIC COOLING SYSTEMS	
Techniques	
Chilled ceilings	Use a radiant panel which requires careful integration into the ceiling design, eg lighting, primary air ceiling diffusers (if used), partitioning layout. Cooling output is 50% radiant and 50% convective at standard office temperatures. The maximum cooling load to be handled by this type of system is of the order of 70 W/m^2.
Chilled beams	Use finned tube heat exchangers which can be of the static (passive) type using natural buoyancy effects or can be fed from a primary air system (active beam) to increase the cooling output through induction effects. The static beam has a cooling output of 80% convective, 20% radiant; this tends to 100% convective with the active beam. The maximum gain to be handled by static beam is approx 100 W/m^2 and by active beam 140 W/m^2. Passive chilled beams and chilled ceilings require a separate air supply for space dehumidification and fresh air. This separate air supply can be in the form of a displacement ventilation (dv) system. Sometimes applied with dv, the downward convective flow can disrupt the orderly flow fields created by the displacement system, thus reducing the dv cooling capacity. Hence, the total cooling of the two systems is not an additive effect. The chilled ceiling offers a large proportion of its cooling in the form of radiant cooling (approximately 50%). Although not perfect, it is least disruptive to the dv flow fields. As for any two systems which are simultaneously controlling the same space, separate controls for these two systems should be installed to prevent any instability occurring, for example to supply air at a constant temperature while using a space temperature sensor A simple system to control the ceiling system.
Environment	
Dry bulb temperature	Chilled ceilings – reasonable year-round control, radiant panel – self compensating, output increases as room temperature rises.
Humidity	Primary air provides dehumidification and, if necessary, humidification. The primary air volume flow would be set to carry summer dehumidification load typically 2-3 ach. Condensation will occur on a surface when the temperature of that surface is lower than the dewpoint temperature of the space and can be problematic with static cooling systems. One major variable is the internal moisture load which includes the occupancy latent load and the moisture from outside air which enters through windows. For this reason, openable windows are generally considered to be undesirable in chilled beams/ceiling systems. Various methods of condensation detection and avoidance exist. This could involve full shut-off, thereby stopping the chilled water flow entirely or by adjusting the chilled water inlet temperature.
Air movement	Reasonable air movement but less lively than 'all air' systems.
Odour level control	Good year-round control is provided by the primary air system.
Air cleanliness	The desired level of filtration can be specified for the primary air system.

APPENDIX – CHECKLISTS

CHECKLIST 8 – STATIC COOLING SYSTEMS *(continued)*	
Space requirements	
General	Space requirement for chillers, heat rejection, air-handling units and risers approximately 3-6% of treated area.
Energy	
General	For the notional building* with maximum heat gain of 70 W/m²: ■ space heating 50 kWh/m² ■ fans and pumps 11 kWh/m² ■ cooling 23 kWh/m² **HVAC-related CO_2 emissions:** For the notional building* with chilled ceilings and primary air: ■ heating 9.5 kg/m² ■ fans and pumps 5.0 kg/m² ■ chillers 10.6 kg/m² **HVAC total 25.1 kg/m²** *(*see note 2 on page 24)*
Fan hours run	Primary air, hours run at full load 2500 hours.
Refrigeration hours run	Chiller hours run at full load between 600 hours to 1000 hours.
Ancillary equipment	Cooling tower fans 1-2 kWh/m² Chilled water pumps 2-3 kWh/m² (constant volume) Condenser water pumps 2-2.5 kWh/m² (constant volume)
Costs	
Capital	Mechanical systems £125-£150/m²
Maintenance	HVAC systems £5-£8/m²
Energy	HVAC energy costs for the notional building are £2.65/m².

CHECKLIST 9 – CONVENTIONAL REFRIGERATION PLANT	
Techniques	
Unitary air conditioners	These are local room units which contain the refrigeration machine in its entirety or 'split' between a room unit and a condensing unit located outdoors. Small hermetic electrically driven compressors using a vapour compression cycle of the reciprocating or rotary type are used which are small enough to fit into the room unit. This family also includes more elaborate arrangements, such as cassette or VRF units, where several room units will be served from a single condensing unit. The closed loop heat reclaim system (Versatemp) bridges the unitary and central plant categories. Typical cooling performance figures for air-cooled machines are: ■ CoP @ full load 2.5 ■ seasonal performance 2.2
Central plant systems	The larger central station chillers may be water or air cooled (direct expansion arrangements). The lower range of cooling loads are usually reciprocating machines with screw machines typically around 750 kW, and centrifugal machines for higher cooling loads. Typical cooling performance figures for air cooled machines are as follows: ■ seasonal performance CoP – 2.5-2.7 and for water cooled machines: ■ seasonal performance CoP – 4.0-5.2
References	
	CADDET. Analyses series No. 15. Energy efficient HVAC systems in office buildings (1995)

FURTHER READING

ASHRAE (Website www.ashrae.org)
- Handbook – HVAC systems and equipment

BRE (Tel 020 7505 6622. Fax 020 7505 6606)
- Airtightness of UK buildings and future possibilities
- BRE Report (BR) 262. Thermal insulation: avoiding risks
- Information Paper (IP) 16/95. The safety and environmental requirements of new refrigerants

BSRIA (Tel 01344 426511. Fax 01344 487575)
- Displacement ventilation
- Dynamic energy storage in the building fabric

CADDET (Freepost A143, ETSU, Harwell, Didcot Oxfordshire OX11 0BR. Fax 01235 433066)
- Analyses series No 15. Energy efficient HVAC systems in office buildings

CIBSE (Tel 020 8675 5211. Fax 020 8675 5449)
- Applications Manual (AM) 2. Window design
- Applications Manual (AM) 10. Natural ventilation in non-domestic buildings

DTI (Tel 020 7215 2697. Fax 020 7215 2723)
- Energy Trends

E&FN Spon (11 New Fetter Lane, London EC4P 4EE. Tel 020 7583 9855)
- SPON's Mechanical and Electrical Services Price Book

ENERGY EFFICIENCY BEST PRACTICE PROGRAMME DOCUMENTS

The following Best Practice programme publications are available from the BRECSU Enquiries Bureau. Contact details are given below.

Energy Consumption Guide

19 Energy use in offices

General Information Reports

30 A performance specification for the Energy Efficient Office of the Future

31 Avoiding or minimising the use of air-conditioning – A research report from the EnREI Programme

Good Practice Case Study

308 Naturally comfortable offices – a refurbishment project

Good Practice Guides

165 Financial aspects of energy management in buildings

182 Heating system option appraisal – a manager's guide

187 Heating system option appraisal – an engineer's guide for existing buildings

274 Environmentally smart buildings – a quantity surveyor's guide to the cost-effectiveness of energy-efficient offices

287 The design team's guide to environmentally smart buildings

290 Ventilation and cooling option appraisal – a client's guide

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