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DESIGN AND OPERATING CONCEPT FOR AN INNOVATIVE NATURALLY VENTILATED LIBRARY

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Recent years have seen increased use of natural ventilation, daylighting, and cooling techniques in UK buildings. This paper describes the design and operating concept of a large, naturally ventilated and illuminated city centre library for Coventry University in the UK. The novel design concept includes four lightwells acting as ventilation inlets, each of which is fed with fresh air from a plenum below the ground floor. A central lightwell and perimeter stacks draw air across each floor plate and provide air extract routes. This strategy enables fresh air to reach the core of the building whilst keeping the external façade sealed for reasons of security and preventing urban noise and pollution.

Computer simulation demonstrates that the building is likely to be well ventilated and thermally comfortable. The building and the analyses should increase the confidence of engineers and architects designing sustainable buildings.

Introduction

Sustainable building design not only aims to maximise the use of environmentally benign materials, but also seeks to minimise greenhouse gas production by reducing the amount of energy required for ventilation, cooling and heating. Appropriate techniques include wind- and buoyancy-driven natural ventilation, daylighting, night cooling and the use of combined heat and power plants.

Temperate climates such as that experienced in the UK offer ideal potential for natural ventilation and cooling due to the moderate air temperatures and humidities during summer. Even when internal air temperatures occasionally peak above 28°C, careful building design makes it possible to achieve a dry resultant temperature below this limit. It has been shown, for example in the Queens Building at De Montfort University (Eppel and Lomas (1991), BRECSU (1997)), that by appropriate design, summertime comfort can be achieved naturally even when internal heat gains exceed 50Wm^{-2} of floor area.

This paper describes the design and operating concept of a large naturally ventilated library currently under construction at Coventry University in the UK. Because of the innovative nature of the design, computer simulation was used to steer the design process and evaluate design proposals.

The Brief

The client (Coventry University) proposed a brief which included the following points, many of which are in keeping with sustainable building design.

a) The building should be fully functional as a library and have a net floor area of about 12000m^2 including an open-access (24 hours per day) computing facility, with an area of about 400m^2.
b) The building should be as energy efficient as possible and environmentally friendly. Full consideration should be given to natural lighting, fresh air ventilation, and combined heat and power.

c) The proposals should be computer modelled to produce the full anticipated running costs.
d) To satisfy the local authority request, the building should be finished in brick and not exceed four storeys.
e) The building should be useable as a teaching vehicle for the University's School of the Built Environment.
f) The internal layout should be simple and thus understandable by its users.
g) Control of noise, both internal and external is essential.
h) The library must be secure.
i) The use of computers is likely to increase rather than decrease so design proposals must accommodate such changes.

The building's inner-city location imposed additional design challenges. Coventry, in the UK Midlands, suffered serious wartime bombing and its reconstruction has resulted in a car-oriented road network. The site suffers from traffic noise and pollution, and is subject to the gusty and unpredictable wind conditions often encountered in inner-city areas.

Environmental Design Study

The client provided an initial sketch proposal for the building, which comprised a large, deep-plan rectangular building with a simple internal layout. It was evident from the design that such an option would require mechanical ventilation and probably air conditioning, and daylit areas would be confined to the building perimeter. The design was used as a base case benchmark against which the energy and environmental implications of other proposals could be compared.

Given the deep-plan form which seemed likely to emerge, computer simulations were undertaken to estimate the likely consequence of mechanical and natural ventilation strategies on the summertime temperatures in the core area. The simulations were performed using ESP-r (ESRU 1996), a combined energy and thermal analysis tool, and consisted of a simple single zone model running for a typical UK summer design day (peak temperature 25.5°C). Results were obtained for four zone types (Table 1): the book stacks, typical library study spaces with anticipated heat gains, study spaces with higher heat gains due to future possible increases in occupancy and use of computers, and the open access computing facility.

Table 1. Maximum dry-resultant temperatures predicted by ESP-r for the library core on a UK summertime design day.

Ventilation description	Ceiling	Maximum dry-resultant temperature: Book Stacks $15Wm^{-2}$ (0600-2100)	Library – anticipated $30Wm^{-2}$ (0600-2100)	Library – future $45Wm^{-2}$ (0600-2100)	24-hour computing facility $60Wm^{-2}$ (0600-2100) $30Wm^{-2}$ (2100-0600)
Natural ventilation from perimeter windows	False lightweight	28.9	35.9	43.2	50.4
Enhanced natural ventilation (e.g. perimeter to atrium venting)	Exposed concrete	26.1	31.5	36.9	42.3
Enhanced natural ventilation with night cooling	Exposed concrete	24.8	27.8	30.7	N/A
Mechanical supply	False	25.3	27.4	29.7	32.1
Mechanical with night cooling	Exposed	23.7	25.4	27.1	N/A

As expected, core spaces cannot be adequately ventilated from perimeter openings and so high temperatures (12°C over ambient) could occur with the anticipated library usage. However, for this usage, enhanced natural ventilation, whereby fresh air is encouraged to ventilate the core (for example, by the use of an atrium), can, provided the concrete ceilings are exposed and night-time ventilation is employed, yield dry-resultant temperatures in the library below 28°C; this is approximately the limit of thermal comfort for naturally ventilated buildings. Mechanical ventilation, which can supply ambient air during the day and night, could provide comfort even under high heat gains ($45Wm^{-2}$). Because night venting cannot be used in the 24-hour computing facility and because of the high heat gains, mechanical cooling is required to ensure comfortable conditions.

Given the client's brief, enhanced natural ventilation rather than mechanical ventilation was pursued, but in the light of the above simulations, various design features were incorporated to produce a library which would be robust to the possible future higher internal heat gains. These included:

a) placing the 24-hour access computing area in a separate, air-conditioned location outside the main library area,

b) locating the areas with highest heat gains, (i.e. lecture and seminar spaces, and work bays with IT equipment), close to the point of cool air supply,

c) locating low heat gain areas such as the book stacks in the more deep plan areas,

d) provision of daylight into the building core to reduce lighting gains as much as possible,

e) appropriate summertime shading of glazing, and

f) intelligent control of ventilation openings using a Building Energy Management System (BEMS), thereby optimising the natural airflow rates.

The architects produced an atlas of six alternative concept designs which incorporated these ideas, in addition to satisfying other practical design requirements. Following discussions of these designs with the client, the final novel environmental concept was evolved.

Architectural Form of the Library

The design studies resulted in a $9000m^2$ four storey building (Figs 1, 2a and 2b), with a square footprint (Fig. 3) measuring $50m \times 50m$ and a top floor with a cruciform shape. A half basement measuring $22m \times 50m$ houses the book archive and the 24-hour (open access) computing facility. The main stairs, fire escapes and fire fighting shafts stand away from the main building to preserve the simple, square open floor plate (Fig. 3).

Lightwells penetrate the building in each quadrant whilst a central lightwell penetrates the upper three stories only (Figs. 2 and 3). Sixteen vertical ventilation stacks are distributed around the perimeter of the building with four additional service and ventilation stacks inside each corner.

Work spaces are clustered around the lightwells whilst the book stacks occupy the deeper parts of the building. The corner areas can be subdivided in a variety of ways to create the required spaces for offices, seminars and lectures, etc.

Intended Ventilation Strategy

Ventilation of all occupied spaces, except the open access computing facility in the basement, is by buoyancy-driven displacement ventilation. Fresh air enters the lightwells in each quadrant passively, through plena below the ground floor. The stale air is then exhausted through the central lightwell and perimeter stacks. These increase in cross-section with height up the building to accommodate the progressively increasing volumes of exhausted air and to help compensate for the reducing stack effect.

The large floor-to-ceiling height of 4m and the use of castellated beams enable stale air to collect above head height and flow towards the perimeter exhaust stacks and the central lightwell. Terminating the perimeter stacks and central lightwell above the roof line enhances this stack effect and avoids unpredictable roof level turbulence.

The airflow rates are controlled by louvres located at the entry level to the under-floor plena, and in the exhaust outlet in each perimeter stack. Openable lights are located at the head of the central exhaust lightwell. Additional airflow control to the individual zones on each floor is provided by low-level openable lights in each corner lightwell and high-level openable lights in the central exhaust lightwell. Louvre operation is controlled by the Building Energy Management System (BEMS) which simultaneously opens the low- and high-level lights on each floor when CO_2 readings from air quality sensors exceed the outdoor level by some pre-set concentration. These lights will be opened further if the space temperature exceeds the desired set-point. The louvres opening into the under-floor plena and the opening lights at the head of the central exhaust lightwell are controlled throughout occupancy hours based on prevailing weather conditions.

The ventilation strategy ensures adequate volumes of fresh air can reach all the densely occupied cellular and open plan spaces without the need to open perimeter windows. Thus day and night venting is possible without compromising security and without the ingress of urban noise and pollution. The airflow routes are also predictable so pre-warming of wintertime air is possible and cold draughts are avoidable.

Intended Winter Operation

The building is well insulated to reduce heating energy demands: external walls (U value=0.26$Wm^{-2}K^{-1}$), roof (U value=0.18$Wm^{-2}K^{-1}$), and low emissivity double glazing to all external windows with argon filled cavities (U value less than 2$Wm^{-2}K^{-1}$). Space heating is by low pressure hot water emitters supplied by a combined heat and power plant (210kW (electrical), 317kW heat) supported by three gas-fired boilers operating in sequence. Panel radiators are used around the perimeter of the building, controlled by thermostatic radiator valves in personal offices, and wall mounted thermostats in larger spaces.

During unoccupied periods, all ventilation openings will be closed and blinds at the top of the lightwells will be closed to reduce radiant heat loss to the night sky. Prior to occupancy the heater batteries warm the air in the air supply lightwells to avoid draughts when the supply louvres open into the occupied zones, and to reduce heat loss from the main library into a cold lightwell. During occupancy periods when the louvres open to provide fresh air, pre-heating of the supply air occurs in the first instance at the heater batteries. The BEMS controls the amount of heat input based on data from a temperature probe protruding into each lightwell. Further pre-heating is provided by trench heaters placed at the low-level fresh air entry point to each floor. Natural light is maximised during the daytime by opening the blinds at the top of each lightwell.

Intended Summer Operation

To ensure daytime thermal comfort, night ventilation to cool the exposed thermal mass of the ceilings can be undertaken by fully opening all inlets and outlets. The decision on whether or not to perform night cooling is taken by the BEMS which possesses a 'self-learning' algorithm which enables it to predict the likely temperature during the following day. The control of louvres at the entrance to the under-floor plena and the outlets at the head of the central lightwell continue to be determined by prevailing weather conditions. The BEMS will prevent over-cooling by fully closing all louvres to any floor on which the slab temperature falls below a set-point of about 18°C.

At the beginning of the occupancy period all louvres will begin to open for fresh air requirements. As occupancy increases, buoyancy-driven flows will be established and the BEMS will control opening sizes based on the air temperatures measured in each zone. During the day, the translucent blinds at the top of the lightwells will be closed to help prevent solar gain and thus unnecessary heating of the supply air whilst still maintaining natural light.

The voids at the top of the supply lightwells can be cross-ventilated to avoid over-heating by opening lights on each side of the void.

If the outside temperature exceeds an 'upper' set-point (say about 29°C), then the louvres are reduced to their fresh air limit to prevent over-heating of the building. Radiant exchange between occupants and the (night-cooled) building fabric is then relied upon for comfort. When the ambient temperature falls below the upper set-point and internal temperature readings dictate, then the openings are again increased to maximise ambient cooling.

As the ambient temperature falls during the late afternoon and evening, louvres are gradually closed to their minimum (fresh air requirement) sizes.

Computer Simulations

In order to confirm that the building would remain thermally comfortable and properly ventilated during the summer period, computer simulations were undertaken. Full details of these simulations are given in Cook et al. (1999); only a summary is given here.

The dynamic thermal simulation (DTS) program ESP-r (ESRU (1996)) was used to construct a combined airflow and thermal network for each of the library floors. Simulations were conducted for a whole year taking account of solar shading, thermal mass and the anticipated internal gains. The results (e.g. Fig. 4) showed that the dry-resultant temperature would always be below 28°C and that 27°C would be exceeded for only 11 hours of the year.

It is anticipated that refined control of airflow using the BEMS (which was not simulated) would be capable of reducing internal temperatures even further. The anticipated impact of BEMS control is indicated in Figure 4.

Computational fluid dynamics (CFD) simulations, conducted using CFX (CFDS (1997)), showed that adequate ventilation flow rates could be established on the lower three floors using the naturally occurring heat loads within the library. On the top floor, a potential over-heating problem was identified caused by a back-flow of air *from* the central lightwell *into* the occupied spaces (Fig. 5). This was due to insufficient stack force in the central lightwell. The result lead to design modifications: the central lightwell was sealed off at the top floor level and dedicated exhaust stacks were incorporated into the top floor ceiling soffit.

CFD simulations for an increase in occupancy of almost 50% indicated that internal temperatures would only increase by about 1°C, owing to the corresponding increase in ventilation flow rate driven by the increased internal heat loads.

Summary and Conclusions

The design of a large naturally ventilated and illuminated library on a city centre site has been described and its intended operation outlined.

A concept study, in which dynamic thermal simulation was employed, concluded that comfortable temperatures were attainable provided that fresh, ambient air could be introduced into the core of the deep plan library, and that exposed thermal mass and night ventilation were employed. Fresh air will be supplied from four lightwells penetrating each of the four floors. This will be fed via plena linked to ambient air at basement level. This approach also reduces the energy demand for lighting and decreases the internal lighting gains which assists natural cooling. Air is exhausted from a central lightwell and perimeter stacks which means that the library perimeter can be sealed to maximise security and reduce noise and air pollution.

Measures such as low *U*-value glazing, the use of combined heat and power, and blinds to reduce radiant heat loss, have been adopted to reduce wintertime energy consumption. The lightwells and clear perimeter glazing admit daylight, reducing the internal lighting gains and so decreasing the risk of summertime over-heating. Other design issues contributing to reduced over-heating risk are: exposed thermal mass and night cooling, a large floor-to-ceiling height, and translucent blinds to reduce solar gain.

Computer simulations of the library design have shown that the natural ventilation strategy is likely to work, and that the thermal environment during a typical UK summer is likely to remain comfortable for both the anticipated and increased library usage. Computational fluid dynamics simulations prompted modifications to the design of the top floor to ensure adequate ventilation and prevent over-heating.

The work has indicated that in the UK, it is possible to design large, nominally deep-plan buildings, which do not require any mechanical ventilation (air-conditioning) to maintain comfortable conditions, despite internal heat gains up to about $40Wm^{-2}$.

Once completed, the library will provide a fine example of low energy architecture, which will strengthen the move towards a more sustainable approach to building design.

References

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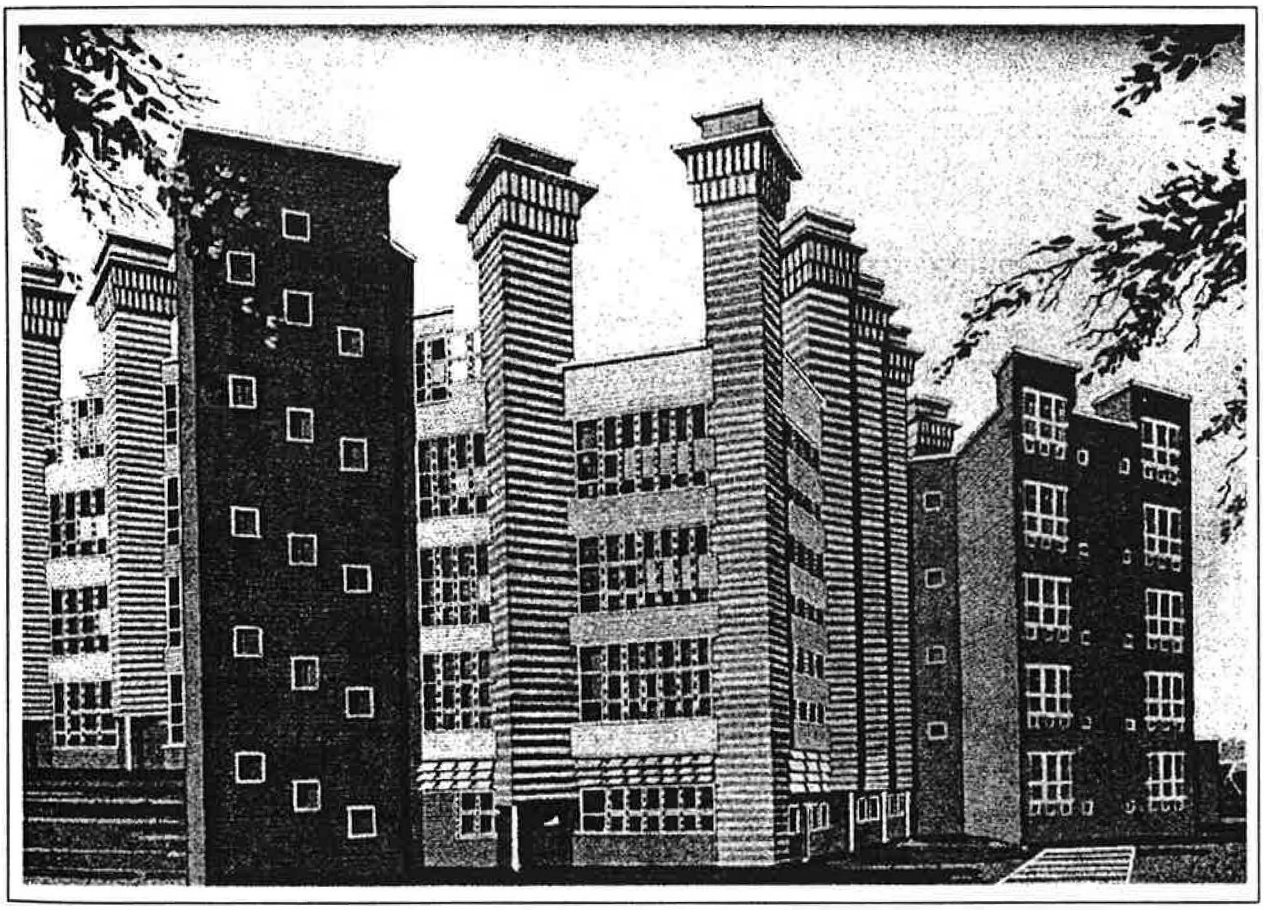

Figure 1. Computer generated image of the proposed library for Coventry University.

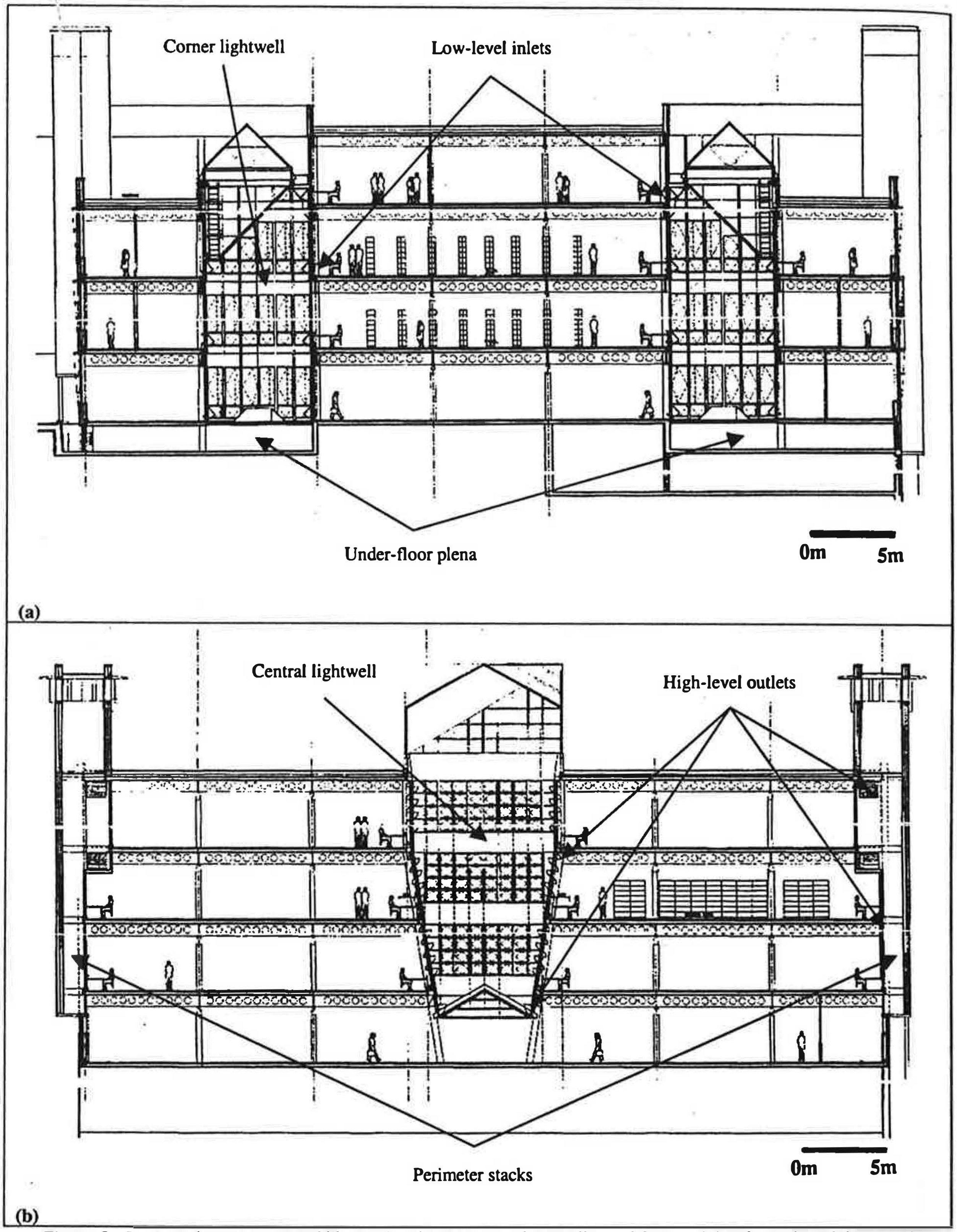

Figure 2. Sections through proposed library showing (a) corner lightwells used for supplying fresh air and (b) central lightwell and perimeter stacks for removing warm, stale air.

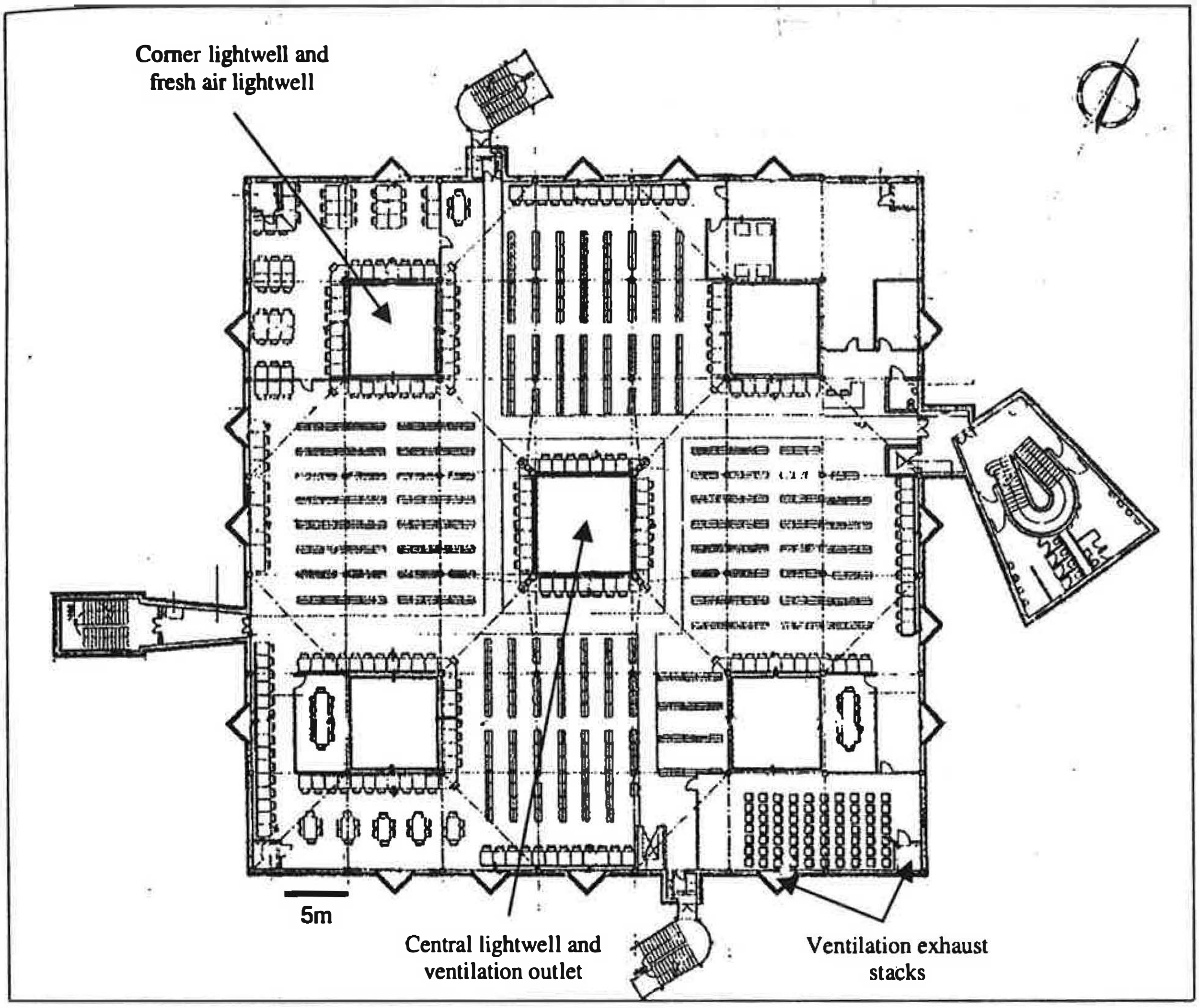

Figure 3. Typical plan of a possible library layout (level 2) showing supply and exhaust airflow routes.

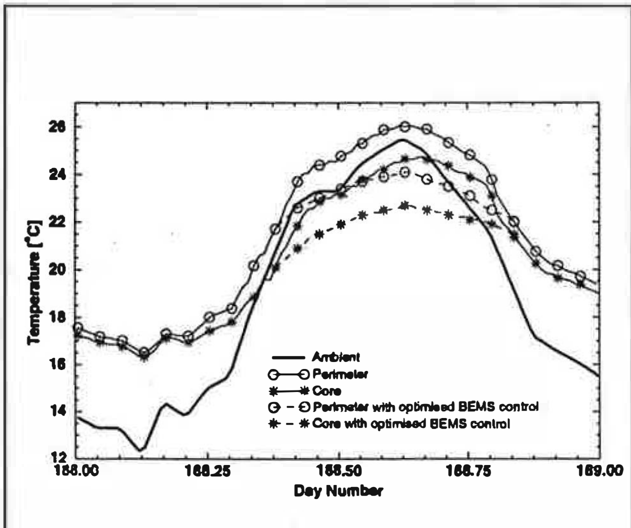

Figure 4. Temperature predictions for core and perimeter areas of the ground floor for a typical hot summer day.

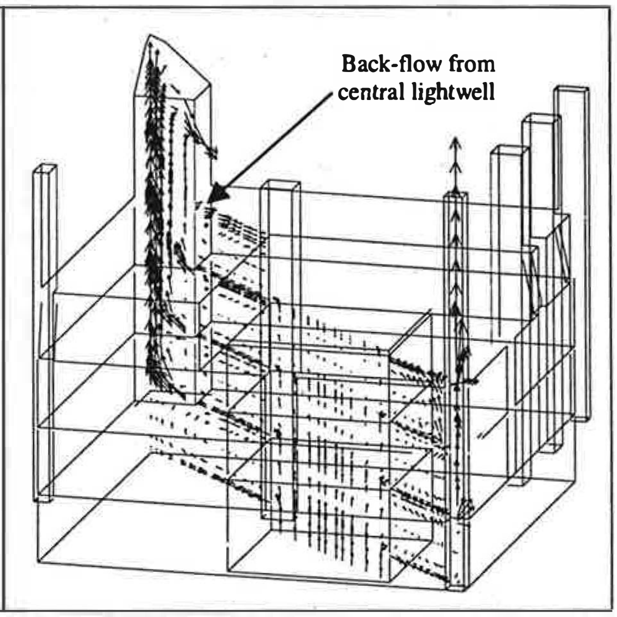

Figure 5. Airflow prediction showing 'back-flow' onto the top floor.