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Commissioning hybrid advanced naturally ventilated buildings: a US case-study

K J Lomas[1], M J Cook[1] and C A Short[2]

[1] Institute of Energy and Sustainable Development (IESD), De Montfort University, Leicester LE1 9BH
[2] Short and Associates, 24 A Marshalsea Road, Borough, London SE1 1HF

Abstract

A new building for a university near Chicago, USA, utilizes a hybrid advanced natural ventilation (ANV) strategy to condition a deep-plan library. The design and construction are described but the paper focuses on the post-construction, pre-occupancy commissioning trials undertaken to test both the active and passive environmental control systems.

These simple qualitative trials confirmed that the ANV strategy functioned broadly as intended but reveal unexpected features of the mechanical systems, faulty components, errors in the control logic of the building management system, and design omissions. Many of these could be readily corrected prior to occupancy thereby improving the likely energy and environmental performance.

The trials highlighted the need for forms of contract and methods of working that enable the integrated working of design teams, especially when designing innovative buildings.

The benefits of adopting simple qualitative commissioning trials, and some of the current barriers to achieving this, are discussed.

Keywords – commissioning, design, natural ventilation, hybrid building

Introduction

Natural ventilation (NV), to maintain indoor air temperatures and thermal comfort, has the potential to significantly reduce energy consumption (and energy costs) compared to the use of mechanical ventilation (MV) and cooling (Bordass et al 2001).

The term 'natural ventilation' usually conjures up an image of a small scale building, with a shallow plan depth, operable perimeter windows and variable and unpredictable internal temperatures, air quality and air speeds. The manual operation of windows can be inconvenient, but on the other hand it has been shown that the provision of personal environmental control can, in part, enhance satisfaction with the building's internal conditions through adaptive opportunity (ASHRAE, 1998) and the 'connectivity' with the outside world can be welcomed. The simple NV strategies are suitable for temperate climates, a site with a benign micro-environment, to buildings with modest internal heat gains and when occupant activities will tolerate variations of internal temperature.

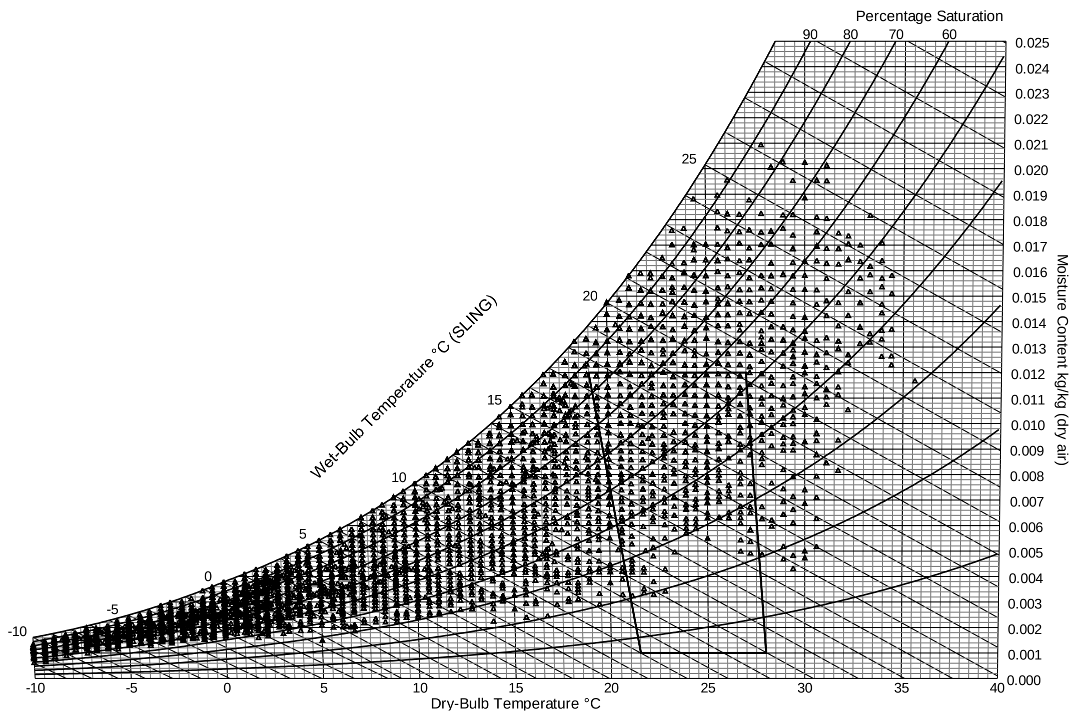
Where such conditions do not prevail, as is the case in much of the USA, where some locations have harsh winters, others very hot (and possibly humid) summers, architects and engineers often revert to sealed mechanically-conditioned buildings. The presumption that buildings will be designed this way has, historically, underpinned US standards; ASHRAE

Standard 62.1 (2004), for example, states that NV systems are permitted 'in lieu of or in conjunction with mechanical systems' but goes on to list pre-requisites that should be met.

There is, however, a growing interest in NV buildings in the US, for instance in the recent publications of Axley (Axley et al 2002) and Emmerich (eg Emmerich et al 2003), and real world examples have also been described (eg Haves et al 2004; Carrilho da Garça et al 2004). The emergence and growing profile of the Leadership in Energy and Environmental Design (LEED) certification system (Green Building Council 2001) supports the benefits of, and should stimulate interest in, NV buildings.

Much of the thinking is, however, strongly influenced by shallow-plan, perimeter ventilated preconceptions. Indeed, whilst ANSI/ASHRAE Standard 55 (2004) now includes an adaptive approach to assessing thermal comfort for free-floating, ie NV, buildings the use of this approach, rather than the use of the standard ASHRAE thermal comfort envelope (Fig 1), is heavily constrained to occupant-controlled naturally conditioned spaces: 'where thermal conditions are regulated primarily by occupants through opening and closing windows'; 'that have operable windows which open to outdoors'; 'where occupants are engaged in near sedentary physical activity' and 'may freely adapt their clothing'; and that have 'no mechanical cooling system'. Brager and de Dear, in their paper of 2001, rue these restrictions, which remain in the standard despite negotiations pressing for a more liberal application of the adaptive approach. Thus, the potential flexibility offered by the standard is not available to hybrid buildings, eg those that use NV at some times of the year and air-conditioning at others, to buildings that control airflow using a building energy management system rather than occupant intervention, or to spaces where openable elements (not necessarily windows) are not connected to the outdoors. This is the case with a whole class of NV buildings; so called advanced naturally ventilated buildings.

Fig 1 Temperature and moisture content in the typical meteorological year for Chicago and the ANSI/ASHRAE Standard 55 thermal comfort envelope (after Lomas et al 2007)



Advanced naturally ventilated buildings

Advanced naturally ventilated (ANV) buildings, like many architectural forms, lacks a formal definition but they are characterised by the introduction of ambient air for ventilation and cooling in a controlled and predictable manner, often using buoyancy forces generated by the elevated internal temperatures to drive the airflow. High level air outlets, often at the head of vertical stacks, enhance the flow, which is controlled by occupants opening windows or by louvers or windows controlled automatically using a building management system (BMS), or a combination of these. Such buildings often combine passive night-time ventilation with exposed thermal mass to provide the necessary summer-cooling of spaces. Four distinct ANV strategies that utilise stacks to enhance airflows have been described (Lomas 2007). Used singly or in combination, these strategies enable deep-plan buildings with sealed facades to be naturally ventilated. Thus ANV buildings can overcome the geometric limitations inherent in conventional NV approaches.

These advantages mean that ANV buildings have attracted the interest of architects in the UK and in Europe more generally. A body of knowledge about how to design such buildings is, therefore, being built up and design terms are acquiring the expertise through work on a succession of ANV designs; one such team includes the authors of this paper working, as environmental consultants, with architects Short & Associates. Since 1992, this team have completed eight buildings with ANV (and others with different partners). Many have been reported either in architectural or building services literature or by the design team themselves, many of the buildings have won awards.

In 2001 the team won the architectural competition to design a new library and faculty building for Judson College, now Judson University, just outside Chicago, USA (Fig 2). The extremely cold winters and warm humid summers meant that a pure NV strategy would not be feasible so a hybrid approach was adopted in which NV was used whenever possible but with mechanical ventilation (MV) in winter and MV with cooling in the hottest part of summer days. Although the buildings have operable windows, as required by the client, the hybrid approach meant that the conventional ASHRAE Standard 55 comfort criterion (Fig 1) applied[1].

The hybrid approach presented some significant challenges: designing a cost-effective building; conveying the design intent to the local US teams; devising a clear and robust control strategy; accurately implementing the control strategy in a BMS; sourcing suitable components; etc. Many of these challenges revolve around achieving integration between the UK concept design team and the US team.

Given the unfamiliarity of these concepts to the US designers and contractors, a post-construction, pre-occupancy commissioning campaign was initiated in which a trials were undertaken to test the operation of the building in both mechanical and natural modes. The exercise proved very instructive and led to some interesting observations about: the performance of hybrid ANV/MV buildings; interactions between design team members; and the actual performance of plant and components. The lessons learned have value beyond this specific project and hence this paper.

It is not possible to describe the entire building or all the commissioning trials undertaken, therefore the focus is primarily on the Harm A Webber Library building.

The Judson building construction

The design intent of the building has been described in Short & Lomas (2007) and the airflow simulation analysis in Lomas et al (2007) therefore only a brief description of the form of the library and its *intended* operating modes will be given here.

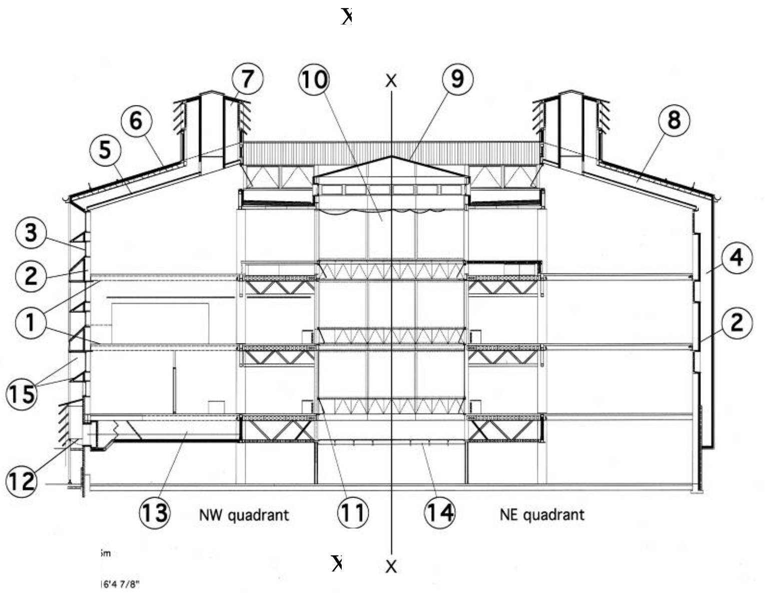
The complete building consists of three main elements, each of which is on four levels, basement, ground and two floors (Fig 2). Facing south are the two wings of the faculty building for the Division of Art, Design and Architecture (DADA) and behind it the Harm A Webber Library, with its square plan (32.9m x 32.9m). The two are connected by the so-called bow-tie section, containing exhibition and teaching spaces.

The buildings have inner walls made of 300mm pre-cast concrete panels which were delivered to site with openings for windows and air inlets and outlets already cut (Fig 3). The panels were externally clad with 100mm of rigid insulation which was then externally rendered. The floors and the ceilings were also of pre-cast concrete panels supported in open steel beams. Thus the building had a high level of exposed thermal mass which, in conjunction with night time ventilation, can provide passive space cooling avoiding the use of -, or reducing the load on -, the mechanical cooling system. The high ceilings, 3.4m on library levels one to three and up to approx 5.5m on level four, and the high thermal mass assist with the natural ventilation strategy, internal temperature stabilisation and night-time ventilation cooling.

The library's central lightwell (Fig 4), clerestory and perimeter windows were of clear double low-emissivity glass. Daylight is therefore admitted to the centre and perimeter of the library with the clerestory providing additional daylight to level four, which is a design studio. The glazed floor of the lightwell admits light into the level 1 semi-basement.

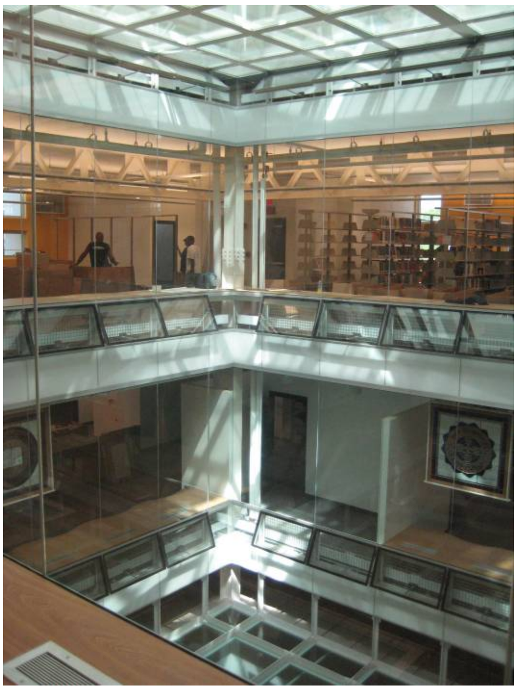
[1] Although the authors (see Short & Lomas, 2007) and Brager & de Dear (2001) indicate that the adaptive method offers no more flexibility than the standard ASHRAE comfort envelope in the Chicago climate.

Fig 3: Construction section through proposed library building, folded about centreline (see section XX on Figure 5 (after Short et al 2007).



(1) Precast floor panels, 300mm (12") overall depth, 37mm (1.5") solid deck, 230mm (9") circular voids, ends grouted, structural topping; (2) Precast wall panels 2.44m (8 feet) wide, 6.71m (22 feet) high, 0.3m (12") thick, solid, with 10mm (4") external layer of rigid insulation, U value = 0.25 W/ m^2K (0.044Btu/ h.ft^2.^oF), inside face painted; (3) Double glazed windows with low emissivity coat and argon filled cavity, U value = 1.85 W/ m^2K (0.326 Btu/ h.ft^2.^oF); (4) Stacks formed independently in ductwork fixed to wall panels, insulated on three exposed sides to U value = 0.27W/ m^2K (0.047 Btu/ h. ft^2 ^oF); (5) Lower deck to roof in precast planks as intermediate floors; (6) Lightweight insulated outer roofdeck of proprietary coated steel sheet on ply deck, insulated to U = 0.25W/ m^2 K (0.040 Btu/h.ft^2. ^oF); (7) Extract termination, steel frame supports lightshaft in marine ply with high gloss white finish, insulated and clad to match roofdeck; (8) Roof plenum formed between inner and outer decks, air-sealed; (9) Lightwell roof double-glazed to U = 1.85W/ m^2 K (0.326 Btu/ h.ft^2. ^oF) with retractable internal blinds; (10) Lightwell in butt jointed single glazing to maximise natural light distribution; (11) Continuous top hung opening lights to each floor to admit air; (12) Air intake at low level supply plenum; (13) Low level plenum formed at underside of internal steel trusses to take precast floor units; (14) Glazed floor to lightwell admits natural light to level 1; (15) White epoxy coated steel linings to window openings.

Fig 4: Lightwell, glazed floor, horizontal glass lens, air inlet slot from plenum and air outlets to each level

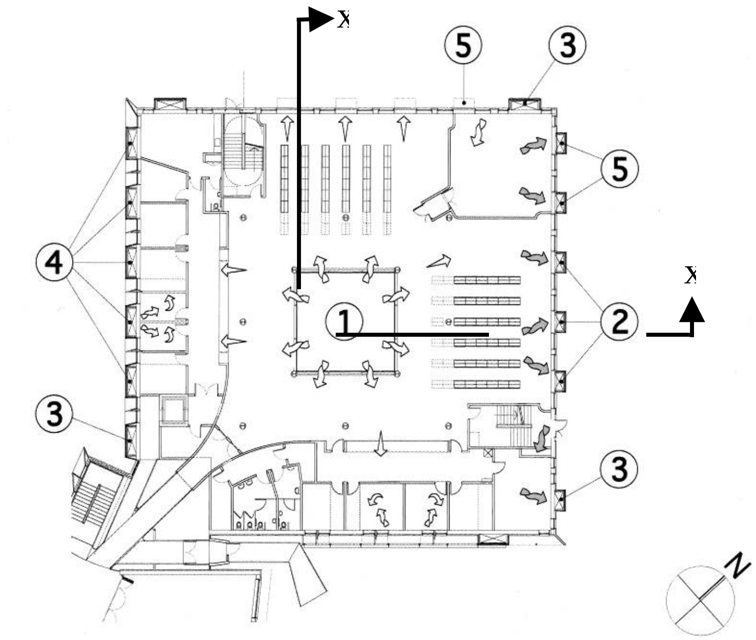


The air extract stacks and air supply shafts around the perimeter were of standard rectangular metal ductwork with external insulation. These were clad with an external face of copper coloured metal. The spaces between the perimeter extract stacks created recesses that shaded the windows during the summer (Fig 2).

Intended ventilation strategy

All three building elements were conditioned using a hybrid approach with one air-handling unit (AHU) serving the DADA wing and bow-tie and another one serving the library. In passive mode, the library uses a centre-in, edge-out ANV strategy[2] for the open plan book stack areas on levels two and three (Fig 5) and the design studio on level four (Fig 6), and an edge-in, edge-out strategy for the offices on the south-east and south-west perimeters (Fig 7).

Fig 5: Proposed level two plan (adapted from Lomas et al 2007).



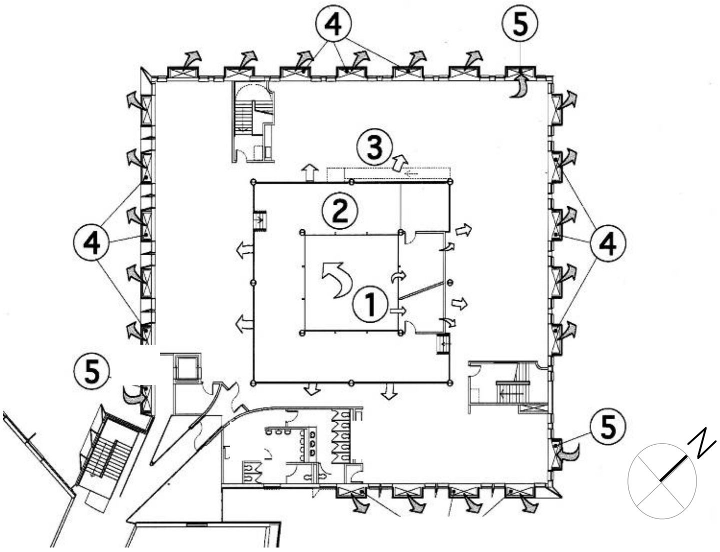
(1) Lightwell air supply; (2) Exhaust air stacks embedded in façade; (3) Return air duct from roof plenum; (4) Rising shafts supply offices on south-west side; (5) Exhaust stacks for classroom in north corner.

For the open-plan areas, the intention is that fresh air will enter the building along the north-west and south-west perimeter through louver-controlled inlets (Fig 8) and then, via a 0.93m deep intake plenum which lies below level two, enter the central lightwell (Fig 4). Fresh air can traverse from the plenum to the south-west perimeter via radiating 'fingers' and so enter the vertical shafts to deliver air to the perimeter offices on levels two and three (Figs 9). The offices on the south-east perimeter are fed from the intake plenum by vertical shafts within the floor plate.

Air leaves the lightwell and enters the open-plan library areas on levels two and three via low-level windows controlled by a building management system (BMS) (Fig 4). On level four, the air from the lightwell discharges below a raised platform (which is approximately 1m off the floor), below which is acoustic baffling to suppress the transmission of noise from the fourth floor design studio to the library floors below (Fig 10). The top of the lightwell is pitched with solar shading below (Fig 3 and Fig 2).

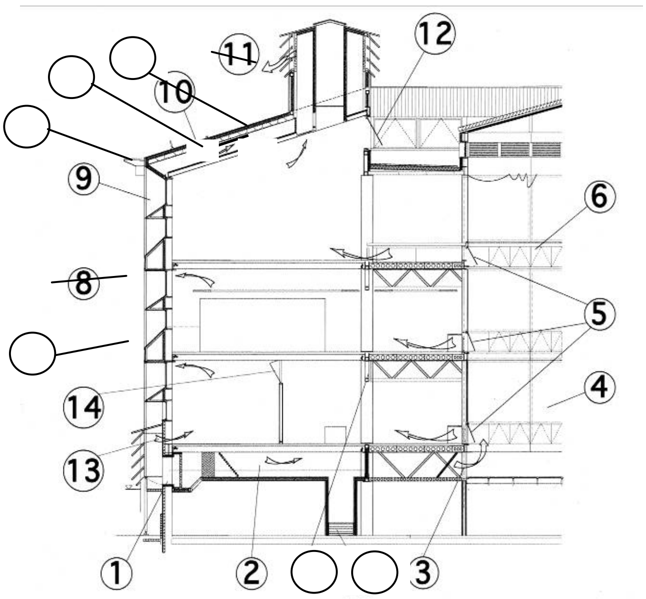
[2] See Lomas, 2007 for a more complete explanation of the four ANV strategies.

Fig 6: Proposed level four plan (adapted from Lomas et al 2007).



(1) Central supply lightwell; (2) Supply air passes through acoustic attenuators and dampers below raised platform; (3) Air enters studio space; (4) Stacks from lower floors bypass level 4; (5) Return air ducts from roof plenum.

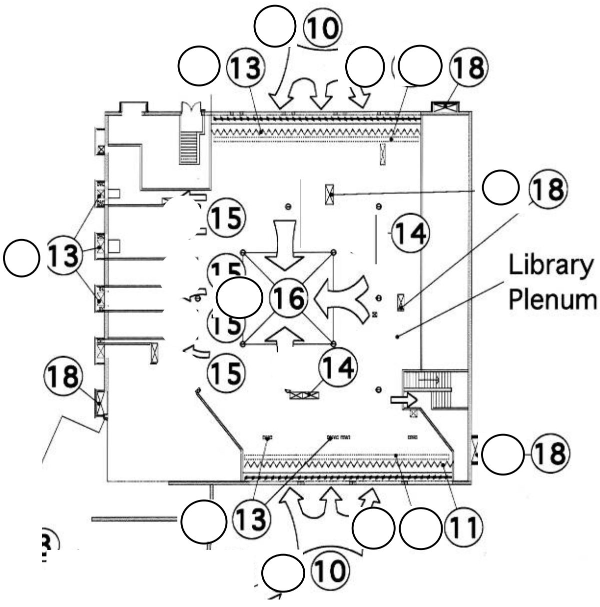
Fig 7: Proposed half section illustrating key features of airflow control (adapted from Lomas et al 2007).



(1) Secure air inlet to building protected from wind and precipitation, louvers provide coarse control only, accessible for maintenance; (2) Smooth, unobstructed accessible plenum; (3) Opening into lightwell on all four sides; (4) Lightwell acts as air supply shaft; (5) Inlets to floors, principal point of fine control of air supply, preheats device behind; (6) Transparent lens, tight sealing to avoid air leakage; (7) Open truss enabling airflow across ceiling soffit; (8) Highest outlet into stack, fine control of airflow by louvers; (9) Vertical, smooth, air tight and well insulated stack, insulated ductwork steel; (10) Gently rising, smooth unobstructed plenum, allows free movement of warm buoyant air, increases stack height; (11) Terminations protected from wind and rain, louvers provide coarse control only; (12) Operable clerestory windows, coarsely controlling additional airflow to top floor; (13) Dedicated supply to perimeter cellular spaces (out of plane of figure), primary fine control of air supply, heater coils behind; (14) Operable window provides an additional, occupant controlled, air inlet; (15) Downfeed from plenum to level one, fine airflow control by outlet dampers, with heating devices; (16) Glazed floor enables daylighting of bottom level; (17) Perimeter based board heating; (18) Outlet dampers at base of turrets provide course control only; (19) Louvers in plane of ceiling.

Fig 8: Louvered air inlets on SE side of the library

Fig 9: Lower plenum level plan



(1) Air intakes to library; (2) Insect mesh; (3) Heating elements; (4) Supply shafts to offices on level two; (5) Supply to vertical air supply shafts; (6) Glazed base of central lightwell; (7) Supply to level 1; (8) Return air ducts from roof plenum to plantroom.

A horizontal glass 'lens' above the air inlet windows to level four separates the top part of the lightwell, which can experience elevated temperatures due to solar gain, from the air space below (Fig 4). The upper part of the lightwell, forms a closed 'greenhouse', which is ventilated via BMS-controlled windows around its external perimeter.

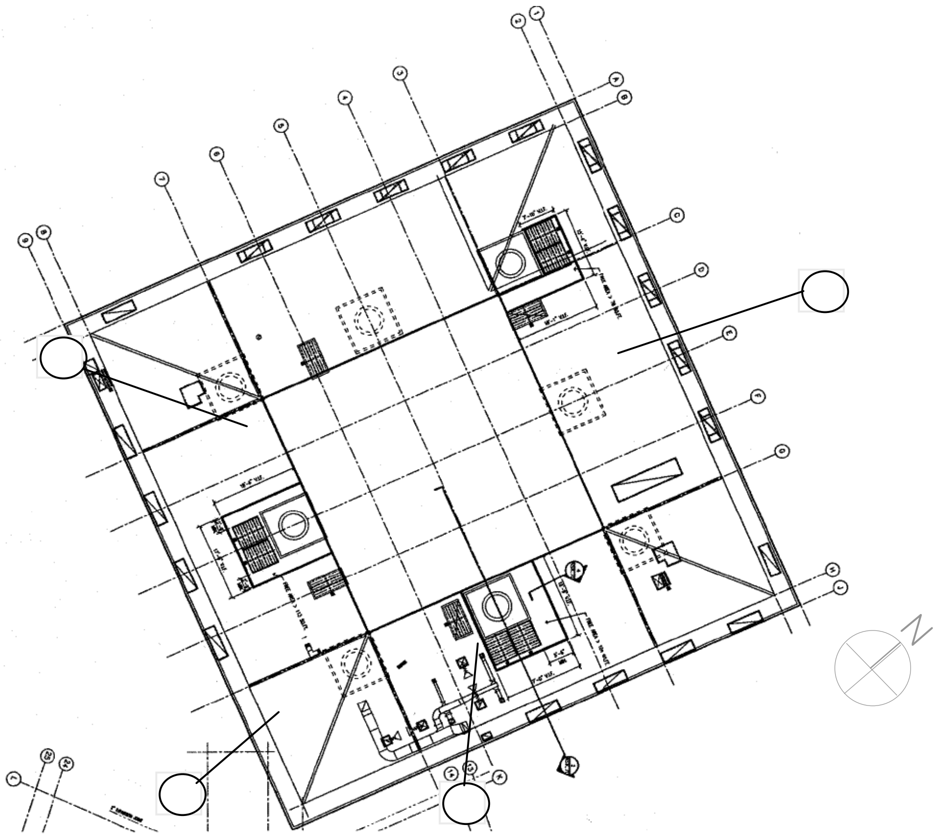
Fig 10: The level four studio showing the raised air inlet (left), the louvered control air outlet to the south-west most turret, the clerestory windows, the perimeter windows and the theatrical smoke machine

The offices on the south-west perimeter are fed at low-level from BMS-controlled louvred inlets in the perimeter supply shafts. The perimeter offices to the south-east are fed from low-level inlets within the floor plate as are the perimeter offices directly above on level three. This edge-in, edge-out strategy enables the offices to be closed to the open-plan area thus maintaining privacy and enabling personal control via the operable windows.

It is intended that all air from levels two and three will be exhausted via the perimeter stacks entering them at high-level below the ceiling soffit. The stacks discharge into the high-level sloped roof plenum located above the ceiling of level four (Fig 7). Particular design care was taken at the junction of the shafts and roof plenum to ensure that air leakage at eaves level was minimised. Air should discharge from this roof plenum via five of the eight roof turrets (Fig 11 and clearly visible in Fig 2). Louvers are located at the point of air entry into the turrets and at the point of exit (Fig 7), the latter should be controlled by the BMS so that the windward opening is closed and the leeward louvers open.

It is intended that the air from level four will exhaust from the three turrets dedicated solely to venting this floor: design work on this and previous buildings had indicated that reverse flow is likely if level four is linked into the roof plenum (ie flow of exhaust air from levels two and three into level four). Louvers controlled by the BMS are located in the plane of the ceiling to enable air to directly access the three turrets (Fig 11).

In mechanical mode, the intention is that the basement plant should draw air in from ambient via a dedicated inlet to the air handling unit (AHU): the air intake louvers to the intake plenum (Fig 8) being closed during mechanical operation. The AHU discharges the air, after pre-heating or cooling, into the intake plenum from where it follows the same routes as in the passive mode. The louvers at the inlets to the perimeter offices and the windows around the lightwell control the volume flows of air. Rather than being exhausted from the roof turrets (the louvers at their base and outlet are closed) and the air is re-circulated from the roof plenum down vertical shafts back to the AHU. Four sets of louvers in the ceiling of level four (Fig 11) allow air from the studio to enter the roof plenum and so be re-circulated. The concept, therefore, is that the architecturally designed airflow paths are used in both the mechanical and passive modes thereby avoiding the need for extensive additional ductwork, etc.



The various planned modes of operation have been described quite fully elsewhere (Short and Lomas 2007). In essence, a BMS system sensing temperatures and CO_2 levels at mid-height on each of the floors controls the opening and closing of the louvers and windows at the air supply and exhaust points. It also controls the space heating, the operation of the AHU and the shading devices and venting windows at the top of the lightwell. On all levels the perimeter vision windows are manually operable; this is entirely compatible with the chosen ANV scheme, and offers occupants, especially those in offices, an opportunity to control their own environment. Actuators on the windows, or warning lights for occupants, to indicate when the building was not in passive mode were not installed.

Space heating is provided by low-level finned pipe elements (base board heating) located around the perimeter of the building and around the lightwell edge where the air enters each floor. Thus preheating prior to occupancy is possible without running the AHU or supplying air passively. The BMS controls space temperatures but room thermostats permit occupants to adjust their individual set-point by up to ± 2^{o}F. In passive mode the fresh air is pre-heated immediately after entering the intake plenum. Night vent cooling is the intended method of maintaining thermal comfort during the spring and autumn and on milder summer days. In active mode the AHU provides the pre-heating or cooling. Because each space has heating and can be passively cooled, it is intended that the air-handling system need only provide the air volumes necessary to maintain air quality rather than the higher volumes required for space heating (or substantial cooling).

Whilst not discussed in this paper, it is relevant to observe that the DADA wing and bow-tie section had a similar design philosophy with a separate air-handling system being used to provide mechanical ventilation to both these areas. The doors between the library and the bow-tie section (Figs 5 and 6) define the line of separation between the areas served by each plant room.

Undertaking the commissioning trials

The commissioning trials were conducted on 19-21 June 2007, the ambient temperatures[3] were in the region of 23 to 25^{o}C and the building was unoccupied except for a few staff members filling the library shelves. During the trials the position of windows and louvers, and the status of the heating elements and air handling plant were set manually through the BMS interface. The purpose of the trials was to test whether the airflow in the building was as anticipated in both the natural and mechanical modes of operation. It was also possible to identify:

- whether the building conformed to the design intent;
- whether components were performing as expected; and
- whether the control strategy had been correctly implemented in the BMS.

The trials also brought the US and UK design teams together (Table 1) and so provided a forum for getting a common understanding about the building and its performance.

Table 1: The design and construction team

Short & Associates – *Architect (UK)*
Burnidge Cassell & Associates - *Architect of Record (USA)*
Institute of Energy & Sustainable Development - *Energy Consultant (UK)*
KJWW - *Mechanical, Electrical & Structural Engineer (USA)*
Shales McNutt – *Cost consultant and Construction Contractor (USA)*
Westside Mechanical Inc – *Mechanical and Electrical Contractors (USA)*
Slaine Campbell - *Landscape Architect (UK)*
E-Cube – *Commissioning Engineer (USA)*

The period after construction but before occupation is an ideal time to undertake such trials: it is easy to move around the building with access ladders, hoists and other equipment; smoke sticks and theatrical smoke can be used without upsetting building occupants; set-points can be changed to achieve desired inside-to-outside temperature differentials without inducing complaints of thermal discomfort; and smoke alarms can be disabled with minimal risk to the building and occupants.

Prior to the trials, a programme of work was drawn up by the UK design team and necessary equipment obtained locally in the US. The pre-programming helped prepare the commissioning team and enabled discussions about the optimal order for the trials, thereby using the three days efficiently. In a heavyweight building, the way spaces are heated or cooled prior to each trial can influence the fabric temperatures and so the inside-to-outside temperature differentials achieved (especially at night); planning can help determine the

[3] Throughout this paper the term ambient refers to the conditions outside the building.

mode of operation of the building in the lead-up to each block of trials. During the trials themselves, the nights can be used to reset and test environmental control settings.

Such planned trial can be useful in identifying problems that can easily be corrected prior to occupancy thereby improving the building's performance. However, within a limited time window it can be difficult to conduct repeat trials after the remedial action has been undertaken. Many potential problems will however require investigation and take more time to rectify. Thus commissioning trials are likely to result in a list of remedial actions to be effected at a later date, possibly post occupancy. The early identification of remedial actions does however enable a schedule of actions to be devised to cause minimum disruption to building users.

All together 21 trials were undertaken covering all three elements of the building (library, bow-tie and DADA): air-tightness tests and mechanical ventilation trials on the first day; and passive airflow trials on the second and third. Problems that could be rectified easily were remedied early each morning and the building put into the mode of operation needed for the first trial of the day.

In general, the trials were of a qualitative nature using the smoke sticks, theatrical smoke generators and hot-wire and vane anemometers to visualise airflows. Temperatures, indoor and out, pressure differentials (during the first day's trials) and other pertinent factors were also recorded. Portable two-way radios enabled communication between the testing team and the BMS controller (who set louvers and windows to the desired position) and between the smoke observers and smoke machine operators. This paper only reports the main results from individual, important, trials and from groups of trials conducted in the library. In the brief three day visit to Judson University it was only possible to test some of the possible operating modes and control sequences.

Air tightness and mechanical ventilation trials

Because the building had an AHU, it was possible to positively pressurise the library by running the unit with the louvers at the intake plenum inlets and the outlets of the roof turrets closed. Level four was the focus of the air tightness trials as it had more potential air leakage paths to ambient than levels two and three. The windows around the lightwell that enable air to enter the other floors of the building were therefore closed. Smoke sticks were used to identify air leakage paths and some flow speeds through apertures were measured with the vane anemometer.

The trials revealed no noticeable air leakage around the clerestory or perimeter windows and only a small number of small gaps between the concrete wall panels and the sloped concrete ceiling. Thus the quality of the wall, roof and window construction, with regard to air leakage appeared to be good. There was however substantial air leakage from the studio into the greenhouse around the loose fitting glass access door. This was unfortunate but could easily be remedied by either draught stripping the existing door or replacing it. Substantial air leakage through the closed louvers in the plane of the ceiling was observed (the pressure differential across them was 16Pa). In active mode most of the leaking air could return to the plant room and thus not result in a significant energy penalty. The leakage was however indicative of a wider, recurrent, phenomenon (see below).

Whilst the building was under pressure, the inlet louvers to the intake plenum (Figs 8 and 9) were inspected[4]. This revealed significant leakage of air as a result of:

[4] Pressure differences of 25Pa across the louvers on the south-east side and 19Pa on the north-west side were generated.

- gaps between louver blades that did not close against each other due to warping or insufficient blade movement;
- gaps due to missing or loose edge seals; and
- gaps because the actuator and lever arm failed to fully and firmly close banks of louver blades[5].

Leakage through these louvers is likely to severely increase the energy demand of the building during both the winter and summer active operating modes. Similar problems were observed at the louvered inlet supplying air to the intake plenum in the DADA wing and bow-tie.

During the trials it was also discovered that the air handling system had no dedicated air exhaust. Thus any fresh ambient air taken into the AHU to maintain air quality would result in the uncontrolled escape of an equal volume of air from the building. Some of this air could escape via the WC ventilation system, the outlet for which has the heat recovery device, but leakage from other areas of the building, in particular through the leaky intake plenum louvers, is highly likely. The positive internal pressures generated by the arrangement will also encourage airflow from the library into the bow tie area. Conversely, air from the bow-tie could be driven into the library (the AHU in this element of the building also lacked a dedicated air exhaust route), especially when the library is in passive mode. This could disrupt the delicate airflows that passive ventilation generates. The use of an air handling system without a purpose made exhaust and heat recovery device is unusual from a European perspective. Given the cold Chicago climate it is likely to lead to excessive heating energy demands.

Passive ventilation trials – level four

The passive ventilation trials were undertaken to test progressively more complex airflow paths using the theatrical smoke to observe the movement of air. During each trial the inside and outside temperatures were recorded, local airflows investigated using the smoke sticks or anemometers, and other pertinent observations made, eg if it was windy outside, if mechanical systems were operating or not.

To test one airflow pattern in the level four studio, the low-level windows from the lightwell and the clerestory windows were opened. During the trial the outside temperature was very similar to that inside so there was no appreciable buoyancy driving force to initiate a passive flow (ambient 25^{o}C, interior 24.8^{o}C[6] - ie probably cooler than ambient), nevertheless some interesting observations were made.

It was anticipated that air would enter from the lightwell and flow out of the clerestory windows. In fact, no flow from the lightwell was discernable but air was observed flowing into level four from the ‘closed’ louvers in the ceiling (which are intended to be an outlet when they are open) and out of the clerestory windows. Inspections revealed:

- gaps between the blades of the louvers in the plane of the ceiling enabling the leakage of air from the roof plenum into level four ;
- gaps between the frames of the louvers within the roof plenum and the surrounding ceiling and roof construction; and
- a set of louvers at the top of a turret which were permanently open.

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[5] The blades when nominally closed could easily be rocked open with minimal pressure.

[6] Temperatures were measured using a hand-held device with a thermo-couple sensor so they are spot measures only. No attempt was made to get an ‘average’ space temperature. As the building was essentially unoccupied temperature stratification was likely to be small.

The observed gaps around louver frames were sealed during the visit and all other frames checked and sealed as necessary. The louvers that were not operating were mended. The leakage of the ceiling louvers was symptomatic of the pervasive louver problem.

During this trial it was also noted that:

- the mechanical systems used to ventilate the WCs created air pressures that disrupted passively driven air flows.

The WCs are located on each floor adjacent to the entrance doors from the bow-tie area (Figs 5 and 6). The air was mechanically extracted from each block of WCs with make-up air being taken from the adjacent (studio or library) area. The air extracted from the WCs was passed over a heat recovery wheel which pre-warmed the incoming ambient air. This pre-warmed air was then discharged into the roof plenum, thereby positively pressurising it. Thus the installed system had the combined effect of creating a positive pressure in the roof plenum and a negative pressure in the studio (and in library levels two and three). The negative pressure could draw air into the library from the bow-tie area (through the connecting doors) and the positive pressures could drive air from the roof plenum out of the ceiling-level louvers and even, potentially, down the perimeter stacks intended to exhaust air from levels two and three. This combination of positive pressure in the roof plenum and negative studio pressure could quite easily explain the flow of air observed in this trial, ie out of the roof plenum (via the leaking louvers) and into the studio.

This observation leads to the more general point, that areas of an essentially passive building which require dedicated mechanical ventilation (WCs, specially conditioned spaces, computer rooms, kitchens, etc) need to be designed so that the substantial pressures that these mechanical systems can induce, do not interact with the passively controlled spaces (which relies on much weaker buoyancy forces to drive flows). In WCs for instance, the positive supply of tempered air into a sealed lobby could provide the necessary make-up air (and permit the integration of heat recovery). Alternatively, under some building codes, WCs can use passive stack venting with the supply of make-up air coming directly from ambient (with suitable pre-heating).

The unexpected WC mechanical ventilation arrangements highlight the importance of good design team interaction over *all* parts of the building (this is discussed more fully below). It would be all too easy, when designing hybrid buildings, to adopt, either explicitly or implicitly, a separation of responsibility for the active systems from a responsibility for the passive systems: with the result that interactions between the two are not properly considered by either party.

Further tests on level four were conducted the next day after the louvers in the turrets had been mended and the gaps around the frames sealed and with the WC ventilation system switched off. The ambient temperature was 24.4^{o}C whilst level four was warmer at 25^{o}C rising to 25.8^{o}C part way through the trials, there was a brisk breeze from the north.

In the first trial the clerestory windows were open by 10% (a crack) and the lightwell air inlets closed. For these tests the studio was filled with smoke on either the north-east or south-west sides. The smoke was observed to clear slowly, but this could be aided by opening the operable perimeter windows; this generated a vigorous airflow. With the low-level lightwell supply windows open and the clerestory open by 20%, and in a separate trial by 50%, the studio cleared of smoke more quickly. There was good airflow from the lightwell and the smoke cleared from the floor level upwards – suggesting achievement of the desired displacement flow regime.

In a further series of trials, the intended principal ventilation path, in from the lightwell and out (via the ceiling-plane louvers) to the turret outlets, was tested. Smoke was injected into the studio space and the clerestory windows closed. There was a rapid clearance of smoke from the studio, beginning from the floor upwards. There was no back flow of air into the studio from any of the ceiling louvers. The smoke leaving the turret in the centre of the south-west side of the library was visible from outside the building. These trials clearly demonstrated that the primary NV strategy for level four worked well (when air pressures were not affected by the WC mechanical system). The alternative ventilation route, from the lightwell to the clerestory, was also satisfactory but this is likely to be more susceptible to the affects of wind than exhausting via the turrets.

The trials did, however, reveal some operational errors:

- the turret louvers were open on the windward side and closed on the leeward side, the reverse of what is intended; and
- the lightwell inlet windows along one side did not operate correctly.

Both of these observations indicate the value of the commissioning trials for checking out the correct logic of a BMS control system particularly in buildings that are particularly innovative. Commissioning of sensors, actuators and control components (louvers, windows, fans etc) can consist of testing whether each component is functioning and responding, as expected, to control signals. This however, does not test whether the different components are simultaneously responding correctly to a number of control signals in order to produce the desired overall building performance; ie in ANV buildings, that the desired air flow paths, with the desired free areas, are operational throughout the building. The control logic to achieve this can be complex, but outside the experience of most BMS and controls companies. The problem is exacerbated because, in the experience of the present authors the mechanisms, for transferring the control intent from the design team, through the M&E engineers, to the specialist control company (and into software logic) are somewhat unreliable (this is an area that could perhaps benefit from a standardised approach). Given these factors, commissioning trials of the type describe here are particularly useful.

Passive ventilation trials – levels two and three

To test the passive ventilation of the level two offices on the south-west side, smoke was injected into them and the air supply route and the air outlet route opened up (ie from the perimeter shafts, into the offices, out at high level into the perimeter stacks, into the roof plenum and out of the turrets). The ambient temperature was 23.2^{o}C and the level two temperature 23.7^{o}C.

Whilst the smoke cleared from the level two rooms:

- some of the smoke entered level three from shared perimeter stacks rather than flowing up the perimeter stacks;
- around a third of the louver blades within the roof plenum, on the south-west side did not close properly; and
- there was unexpected backflow, from the roof plenum into the studio via the leaky closed louvers.

The first of these could easily be because there was no heat being generated in level three to drive an airflow, and thus the inside to outside temperature differential was very small. Also, the incorrect operation of the turret outlet louvers (ie windward louvers open – see above) could induce such an airflow reversal.

The third of the above observations indicates that, contrary to the design intent, the louvers in the ceiling of level four were not linked only with the three dedicated turrets intended to vent level four. Instead there was a direct air path between level two (and level three) and level four: a path which simulations had indicated was liable to cause backflow onto level four. Investigation revealed that the roof plenum had not been internally partitioned as intended to separate the exhaust route from level four from the route from levels two and three.

This experience illustrates that it can be difficult to carry design intent right through the design process. In the case of this project, this required good coordination between the two architectural teams, and whilst such coordination was generally very good, the fault in interpreting the UK concept drawings into the US construction drawings occurred and was not picked up prior to construction. The roof plenum is however accessible and the problem has since been rectified by internally partitioning the plenum so that three air outlet turrets are indeed linked directly to the ceiling outlet louvers from level four and not to the roof plenum that serves the lower three levels of the building (Fig 11).

A trial in which smoke was injected into the room on the northern corner of level two revealed no back flow onto level four and smoke was observed exiting the turrets.

Finally, the flow of air right from the intake plenum, up the lightwell, into levels two and three and out via the roof plenum and turrets was tested; this required the generation of a lot of smoke in both the north-west intake plenum and south-east intake plenum. Smoke was seen to move up the lightwell and into levels two and three and into the offices on the south-east side of level three. Ventilation of the space therefore appeared to be satisfactory.

The smoke injected into the plenum inlets did, however, tend to billow out of the intake plenum on the leeward side of the building. This problem can have energy consequences when, as in the Judson Library, air is preheated at the point of entry into the intake plenum - the energy is simply lost from the building before it can usefully heat spaces. The difficulty can be alleviated by controlling the inlet louvers in response to wind direction, but this is complicated by the swirling nature of winds around the base of buildings. The UK design team are aware that the design of an air intake plenum so that it is not susceptible to wind effects represents a design challenge.

Discussion

The experiences with the Judson building illustrates the benefits to be gained by undertaking thorough pre-occupancy commissioning trials in ANV buildings:

- unlike post-occupancy commissioning, the trials are not constrained by the need to maintain the levels of comfort, security and safety required for an occupied building (heating can be turned up to create required inside-to-outside temperature differentials, smoke can be injected, smoke detectors disabled, venting systems can be turned off and windows opened - despite creating draughts, etc);
- the investigation of unexpected behaviours can be easily undertaken (ceiling hatches opened, plena entered, smoke sticks used, etc); and
- the numerous members of the design team can be assembled, whereas post-occupancy design teams tend to disband - this can improve the common understanding of a building and its environmental performance.

The results of the trials benefit both the building, by enabling performance improvements, and the design team members, who can carry the experiences through to future projects.

Buildings using ANV have the great advantage that the points at which airflow is controlled are generally both visible and easily accessible; which may not be the case with mechanically-conditioned buildings and buildings with false ceilings, raised floors and other cavities. Thus, as illustrated by this study, relatively crude qualitative pre-occupancy commissioning trials and simple visual observation, can readily identify operational faults some of which can be easily rectified before the building is occupied.

Many of the problems observed in the Judson trials - poor louver performance, incorrect control logic and incorrect constructional detailing (the roof plenum partitioning) - stem from the contractual arrangements and cultural norms that prevail in the design and construction industry: these act counter to the ways in which building professionals need to interact when designing innovative buildings.

In the UK, USA, and elsewhere, there is an endemic tendency for aspects of a building's design to be incorporated into physically defined packages that also correlate with each project member's responsibilities; and such packaging is seen as a virtue. Thus an architect designs the building fabric, the M&E consultants devise a suitable space conditioning system, and the structural engineer devises the building structure. The packaging up of roles and responsibilities in this conventional way can make it particularly difficult to design buildings, such as those with ANV, in which the topology, construction and mechanical engineering need to be highly integrated.

Members of a design team generally progress their work in parallel, advancing, to a large extent, on the basis of assumptions about what other partners need and what they will produce. These assumptions develop over years of experience on a number of projects. However, when they are based on experience of conventional, rather than innovative buildings, the assumptions can simply be wrong and act as a barrier to successful innovation[7].

In the case of the Judson project, the physical separation of the US and UK design teams added to the difficulties of achieving integration of thought and deed. The absence of the partitions in the roof plenum, for example, occurred in the transfer from UK concept design drawings and briefings to US construction drawings; a hybrid design can exacerbate the adverse consequences of packaging out individuals' roles. The lack of a dedicated air exhaust route from the AHU, and the absence of heat recovery, would surely have been detected with better interaction and the stated imperative of specifying air tight louvers was either not appreciated or, perhaps, the specified louvers were considered to be air tight enough! The need for a self contained and balanced supply and exhaust to WCs and other mechanically-conditioned areas, is a lesson that needs to be transferred to the design of all ANV buildings.

Despite the potential benefits of commissioning, the typical programming of building projects militates against adequate, or even basic, pre-occupancy commissioning in at least three ways. Firstly, there is pressure, both commercial and from the client, to reduce the length of construction programmes. Commissioning trials take time and cost money and clients often wish to occupy a building even before practical completion and such demands are hard to resist.

Secondly, in the UK at least, it is expected that the time for commissioning and testing buildings will be minimal, late in the construction programme and, in practice, squeezed even further by construction delays. As this is the norm, commissioning engineers, M&E engineers and others are not in a strong position to complain, or do anything about it. It is simply 'generally understood' that this phase of work will be undertaken during occupancy (although prior to practical completion).

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[7] Of course, where the assumptions are based on years of joint working between project partners, it becomes possible to design with confidence highly innovative and successful buildings.

Thirdly, there is an inherent reluctance by design teams to press for a thorough commissioning and testing period and certainly for a long and elaborate set of trials – but for novel buildings such commissioning is all the more important. To do so could convey doubt about a building's design and the ability of the team and so imply added risk for the client; this could risk losing the contract. And yet innovation, which clients might have explicitly opted for, does have associated risk. Drawing an analogy with the automotive industry, such behaviour it is like buying the first prototype of a new car, built by a group of engineers and designers that might not worked together before, which has never been road tested, and then setting off on a long journey. This would be seen as highly risky but it is exactly what the clients of multi-million pound/dollar buildings do all the time.

What is needed is for plans of work and forms of contract that require a *thorough* commissioning phase. Fortunately, there are signs that the need for this is being recognised, for example, commissioning trials are included in the US LEED certification scheme (Green Building Council, 2001). However, such trials could easily become a simple sequence of mechanistic operations simply checking whether each component is functioning and responding, as expected, to control signals. Such routine commissioning does not demonstrate that design and control concepts are actually achieved in practice and certainly does not enable control strategies to be refined in the light of the measurements made.

In an era when CO_2 emissions from buildings are of great concern, and knowing that commissioning, monitoring and management can significantly reduce a building's energy use, perhaps statutory instruments requiring thorough pre-occupancy testing will emerge. In the meantime, as this paper illustrates, there is value to be gained, for both the clients of buildings and building design teams, by undertaking commissioning trials; this is particularly so for innovative buildings.

Conclusions

There is great benefit in conducting thorough post-construction, pre-occupancy commissioning trials in all buildings. Such trials test that the design and control of a building is as intended and can lead to improvements in control and even design. Unlike post-occupancy commissioning, such trials are not constrained by the need to maintain the levels of comfort, security and safety required of an occupied building. Investigations can be undertaken without disrupting the building's functioning.

Commissioning trials are most valuable when the level of innovation is high, such as in advanced naturally ventilated and hybrid buildings; in such buildings, accurate communication between design team members, that achieves real mutual understanding, is more difficult.

Whilst advanced naturally ventilated buildings could be seen as complex, because they are alien to the experience of most building design professionals, they have the great advantage that areas critical to their satisfactory operation are generally both visible and easily accessible. Thus relatively crude qualitative commissioning trials and simple visual observation can readily identify operational faults and these may be easily rectified.

The presence of mechanical ventilation systems, eg extracts from WCs and catering areas, in an otherwise naturally ventilated building, can have an adverse impact on the delicate passively generated driven airflows. It is suggested that such areas should have a balanced ventilation system and that parts of a building that are mechanically ventilated should be well isolated from parts that are passively ventilated.

Mechanically controlled windows and louvers are critical to the maintenance of thermal comfort and energy efficiency in advanced naturally ventilated buildings. Windows tend to operate more reliably and produce an air-tight seal when closed. Louvers tend to be less reliable and can be very leaky even when supposedly closed; smaller louvers may perform more reliably. High quality louvers with a capability to remain air tight over their life-time must be specified.

Many of the problems observed in the trials, poor louver performance, incorrect control logic and incorrect constructional detailing (the roof plenum partitioning), stem from the contractual arrangements and cultural norms that prevail in the design and construction industry.

Perhaps, over time, the description of advanced natural ventilation concepts and designs will become more standardised, and the design, construction and control principles will become more widely understood. Nevertheless, post-completion, pre-occupancy testing will remain important to ensure that buildings perform well for both the client and the occupants.

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References

ANSI/ASHRAE (2004), Thermal conditions for human occupancy, American National Standards Institute (ANSI), American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE), Standard 55-2004, 170 pp.

ASHRAE (1998), Field studies of comfort and adaptation, American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) Transaction Data Bulletin 14.

ASHRAE (2004), Ventilation for acceptable indoor air quality, American Society of Heating, Refrigeration and Air-conditioning Engineers, Standard 62.1-2004, 44 pp.

Axley JW, Emmerich SJ and Walton G (2002), Modeling the performance of a naturally ventilated commercial building with a multi-zone coupled thermal/airflow simulation tool, ASHRAE Trans, Vol 108, Part 2, 16 pp.

Bordass B, Cohen R, Standeven M & Leaman A (2001), Assessing building performance in use: energy performance of the PROBE buildings, Building Research and Information, Vol 29, No 2, pp 114-128.

Brager GS and de Dear R (2001), Climate, comfort & natural ventilation: a new adaptive comfort standard for ASHRAE Standard 55, Proc Moving thermal comfort standards into the 21st century, Oxford Brookes University, Windsor, April, 18 pp.

Carrilho da Garça G, Linden PF and Haves P (2004), Design and testing of a control strategy for a large, naturally ventilated office building, Building Services Engineering Research and Technology, Vol 25, No 3, pp 223 – 239.

Emmerich SJ, Persily AK, Dols WS and Axley JW (2003), Impact of natural ventilation strategies and design issues for California applications, including input to ASHRAE Standard 62 and California Title 24, national Institute for Standards and Technology Report NISTIR 7062, 22 pp.

Green Building Council (2001), Rating system version 2.0, US Green Building Council, Leadership in Energy and Environmental Design, June, 41 pp.

Haves P, Linden PF and Carrilho da Garça G (2004), Use of simulation in the design of a large, naturally ventilated office building, Building Services Engineering Research and Technology, Vol 25, No 3, pp 211 – 221.

Lomas KJ, Architectural design of an advanced naturally ventilated building form, Energy and Buildings, Vol 39, pp 166-181, (2007), ISSN 0378-7788.

Lomas KJ, Cook MJ and Fiala D, Low energy architecture for a severe US climate: design and evaluation of a hybrid ventilation strategy, Energy and Buildings, Vol 39, Iss 1, pp 32-44, (2006), ISSN 0378-7788.

Short CA & Lomas KJ (2007), Exploiting a hybrid environmental design strategy in a US continental climate, Building Research and Information, Vol 35, No 2, pp 119-143, ISSN 0961-3218.