The effects - for good and ill - of building services and their controls

Chairman (Professor Patrick O'Sullivan)
I'd like to introduce Bill Bordass of William Bordass Associates who, like all good services engineers, started life as a Cambridge physical chemist and who was also once my colleague, Professor of Building, at University College London. So here is Bill on the effects of services, good or ill.

Dr William Bordass
Well from Geoffrey to me is probably from the sublime to the ridiculous. Geoffrey used slides and I'm going to use overhead projections; this is a bit more of a lecture, I'm afraid. I'm going to talk a bit more about the internal environment in buildings and how that is influenced at various times by changes in services, changes in uses and changes in ventilation.

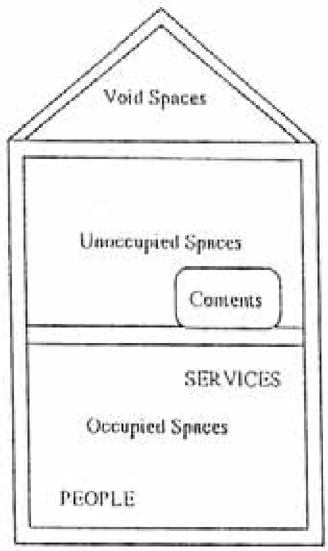

Figure 1. Changing equilibria

Figure 1 shows a building simplified to a very few spaces. It has a climate outside, occupied spaces with people doing things in them and services doing things about them. There are also unoccupied spaces which are common in historic buildings; in National Trust Houses, only a quarter of the rooms are on show, and there's a no-man's land in between which may be holiday flats. There are also the void roof spaces. These are all exchanging heat, moisture and air. All these things wobbling around and varying against each other produce a dynamic equilibrium. In many buildings, over many years, it has been found that the sort of equilibrium pertaining has allowed the building to survive reasonably well. Then something changes; there's a change of use in a house. For example, one lady and her retinue of two servants used to live in it. Suddenly, people move into the house, but they don't make quite enough money out of it, and so they have banquets and conferences, and they introduce a restaurant and a shop. Many things change: they take the fireplaces out and brick them up and put in central heating; the roof gets insulated. All these things affect the interactions, and things may not be the same as before.

Equally, we get disillusioned with what we built in the 1960's and return to traditional buildings and materials. We start using things like brick and lead, but they don't seem to be behaving as they used to because they are no longer quite the same, and the system of buildings, services and occupancies to which they are exposed may be different from that in which they were historically reliable.

Today, I want to deal with modern buildings, old buildings with fairly intensive use (which are often laboratories for decay in modern buildings) and old buildings with less intensive use, particularly churches. I want to look at some of the origins of environmental change under four main headings.

Function

CHANGE OF USE

INTERMITTENT OR PARTIAL OCCUPANCY

LARGE GROUPS OF PEOPLE:
tourism, functions etc.

Environmental control

CHANGES TO HVAC SYSTEMS:
installation, operation, control

ATTEMPTS TO SAVE ENERGY:
insulation, reduced ventilation, intermittency

Different technologies

Less maintenance & caretaking

Figure 2. Origins of environmental change in historic buildings

Figure 2 shows the function of things: changes in the uses of buildings; changes in occupancies; different environmental control systems and attempts to save energy. Changing technology can be applied to both service technologists and construction technologists. In spite of what we hear about intelligent buildings, there is often less intelligence. I've visited churches occasionally to find that the church warden there knows a bit about the building. When it has been cold and then there is a dry day, he throws all the doors open. He knows that the roof drips occasionally but that provided he keeps the gutters clear, problems won't arise. But increasingly, buildings are opened up and serviced when people are there and then shut up and ignored otherwise. So the intelligent management of buildings which used to be present has been fading away; we may now be able to put some of this intelligence back with electronic systems. It may be possible not to use the sledge hammer method of throwing vast amounts of engineering services, money and energy at the problems. With intelligence, we can use the natural environment and let it through the building when it's beneficial but keep it out when it isn't. This would be possible with simple management systems like opening and closing windows, coupled with more intelligent systems which measure and inform.

The environmental variables which are influenced by all these interactions are shown in Figure 3. The four categories consist of: temperature, humidity, air movement and, of course, the timing of these things. Some things occur very quickly. If lots of people fill this lecture room, the temperature rises rapidly. Other things occur slowly. A building may have been perfectly happy over a period of time although it's been slightly damp or dry sometimes. Then something happens which leads to a big accumulation of moisture. Gradually, the scales tip over and the equilibrium is lost. This gradual tipping may take a long time and be almost impossible to detect over one day. Potentially, you may be able to get a handle on it if you can measure over a longer period of time. Then you can set the alarms off.

TEMPERATURE:
Air Temperature
Radiant Temperature

HUMIDITY:
Moisture generation and removal
Relative Humidity
Absolute Humidity
(or vapour pressure or dew point)
Moisture levels in fabric and contents

AIR MOVEMENT:
Natural ventilation
Forced ventilation
Wind-induced infiltration
Buoyancy-induced infiltration
Services-induced ventilation

TIME

Figure 3. The variables

People are interested in two facets of temperature. They normally take a thermometer into a room, wave it around and say, 'That's the temperature', but the amount of radiation coming from surrounding surfaces is also important. So for instance, if you heat a church that's been stone cold all week using warm air, you have to make the air an awful lot warmer to feel as comfortable as that same temperature in your living room. If you had a radiant heater, then you'd be comfortable at much lower air temperatures.

But buildings aren't terribly interested in temperature but rather in how wet they are, which depends indirectly on the temperature. Quite often people only think in two ways. First, is there an obvious damp patch? Second, they stick a meter in the wall, get a high reading and say, 'Yippee, it's damp.' Sometimes it isn't; they hit a bit of metal or salts. There is also absolute humidity: the amount of moisture within the air. The patterns of moisture generation and removal are also important; you have to consider the whole of that system if you're going to get a handle on these environmental changes.

Air movement can happen in many ways. Natural ventilation occurs when the windows are opened, but the air path often changes quite substantially within the history of the building. Forced ventilation from fans ventilates the parts of the building where their operation is wanted, as well as the parts that other things cannot reach. An extractor fan has to draw air from somewhere, which then has to go out somewhere. It may cascade through spaces on its way through the building, transferring air, heat and moisture on the way across. With the use of infiltration, the wind blows against one side of the building and sucks against the other, causing the air to go across. Frequently, buoyancy is introduced. If it's warmer inside the building, the warm air rises, going in at the bottom and out at the top. This is one of the reasons why under floor spaces which have ventilation bricks on either side are sufficiently well ventilated to avoid rot and decay. The outside air does not go in one side and out the other; it goes in both sides and comes through the floor boards in the middle. If the floor boards are covered up, there will no longer be enough capacity on either side; so the moisture level will go up, and rot takes place.

So services reduce ventilation and change the pattern of moisture movement in buildings. Some things occur on short time scales, and some things occur on long time scales.

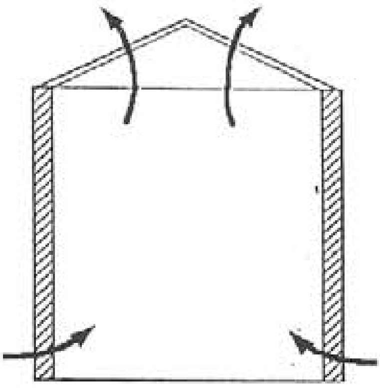

Figure 4. Effect on roof voids

Let us look at something simple such as a roof void (Figure 4). If there are people in the building, then the air will rise inside it and want to pass out through the roof void. Maybe it is sealed up in order to stop that happening. Perhaps the building used to have coal fires in it which drew in quite a lot of air; the air in the building wasn't necessarily rising up through the roof void, but the building was under negative pressure. Much of the outside air would have been drawn in through the roof void in the same way that it was drawn in through the floor boards. So one may find that many mechanisms which happened in the past or before a change are not the ones described in the text books.

What do we do about preserving the fabric and the contents of the building (Figure 5)? There are many rules relating to relative humidity in the air to avoid it getting too high. A normal museum should be kept at 50-60 per cent, although it may not be appropriate for everything in museums. Some things have come from a damp environment like the Mary Rose. The last thing that they want is to be put in a 50-60 per cent environment. Avoid relative humidity getting too low because items can shrink and crack. Avoid it jumping around because organic materials move as moisture content goes up and down. Relative humidity is often the only way people tend to think about moisture in the environment.

Although preferably stable,
Temperature isn't very important

BUT HUMIDITY IS:

Avoid high relative humidities
IDEALLY ABOVE 70%, PRACTICALLY ABOVE 80%
to reduce dampness, condensation,
mould and insect attack

Avoid low relative humidities,
IDEALLY BELOW 50%, PRACTICALLY BELOW 40%
if materials are vulnerable to shrinkage

Minimise relative humidity fluctuations
PARTICULARLY IF SURFACE MATERIAL IS VULNERABLE

Figure 5. Preserving fabric and contents

IT ONLY CORRELATES WITH
MOISTURE LEVELS IN MATERIALS
WHEN IN EQUILIBRIUM

IT CHANGES WITH TEMPERATURE

IT VARIES WITH LOCATION

IT CAN VARY RAPIDLY WITH TIME

IT IS NOT THE
WHOLE STORY

Figure 6. The tyranny of relative humidity

I'd like to bring in a few more variables with reference to a little bit of science. I hope to reduce the tyranny of relative humidity in many people's thoughts (Figure 6). People often go into a space taking a hydrometer, which they whizz around, look at and say, '50 per cent, that's fine', or they say, '30 per cent, that's bad.' In fact there is much more to relative humidity. It's a very complicated variable and even though it correlates with moisture content in materials, it only does so when everything is in a laboratory cabinet and well equilibrated. When the temperature for the same body of air changes, the relative humidity changes. So it's a dependent rather than an independent variable. It can vary with location and will vary with height and proximity to the walls within the room as heat is lost or gained; it can vary rapidly at times.

Let's first look at the definition of relative humidity and what it means in relation to building materials. If a bit of building material is put in an environment where the relative humidity equals x per cent, then a dynamic equilibrium will be set up where moisture evaporates from the material into the environment and condenses from the environment into the material. If this is put into an isothermal box at t degrees centigrade and left there for a few weeks, there will be an equilibrium moisture content in the material which is related to the relative humidity in the environment. What happens if the relative humidity changes? If relative humidity increases, there will be a change in the equilibrium and a net inward flow of moisture into the material so that a new equilibrium is established. If the material is heated up, there will be a net flow out until the equilibrium is established. If the material is cooled down, there will be another net flow. So the theory that what's going on in the building and its contents is related to the relative humidity in the air only tells a small part of the story. This is because you have to say when, under what conditions and for how long. Time constants for the transfer of moisture in units of weeks, months and even years apply to modern constructions but particularly to older and massive buildings. With time, many things have changed: the climate has oscillated; the sun has been in and out; people have been in and out and services have been switched on and off. Everything is dynamically changing and exchanging moisture one with another. Relative humidity is just a link in all this coupling.

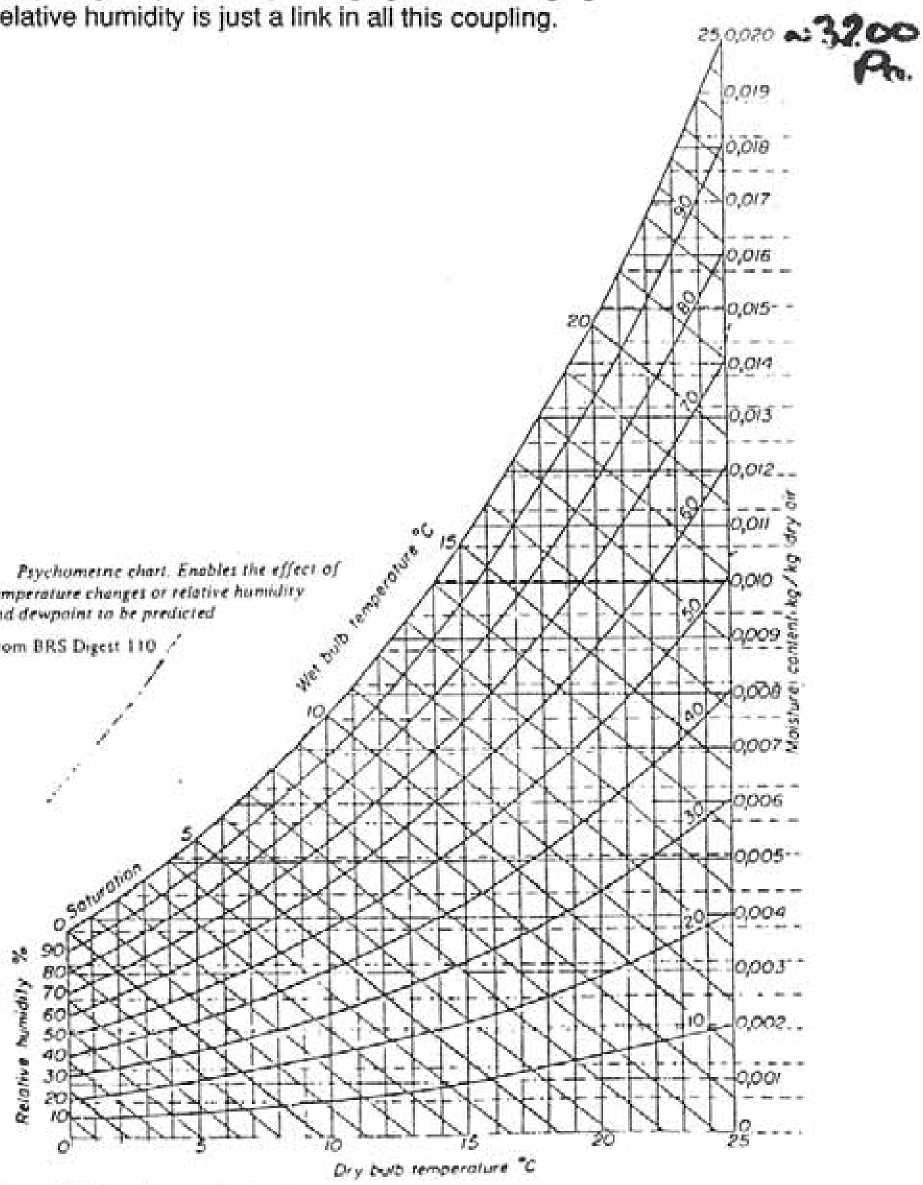

Figure 7. Psychometric chart

We must think about where this moisture is and what it's doing; there's a very tried, tested and proven science involving the use of a psychrometric chart. Frequently, I find that people will come with a problem related to moisture or condensation in buildings, but they haven't thought the whole dynamics through. They think that because it's heated it must be dryer, or because it's heated it must be damper, or because something is ventilated it must be dryer or damper, or it must stop condensation or promote condensation. The actual dynamics of the situation must be looked at to determine what might be going on. The curves in Figure 7 represent a graph with centigrade temperature along the bottom and show normal internal environmental conditions from 0°C to 25°C. Up the side, the percentage of water vapour by weight in the air is shown. Alternatively, vapour pressure or some other variable depending on the amount of moisture in the air might be shown.

It is important to understand the concept of a saturation curve. If some water is placed in the bottom of a sealed container and brought to equilibrium at a given temperature, then there will be some water vapour in the air. If the water in the sealed container is heated to 5°C, there will be just over 0.5 per cent of water vapour by weight in the air. At 15°C, there is nearly twice as much: something around 1.1 per cent. So by raising the temperature of this identical system, twice as much water is evaporated into the air than the water lying underneath. So to start with the air was saturated at 5°C; then the water was removed from the water vapour in the air above the water and it was heated to 15°C; the extra water is not going to come from anywhere. So it has been reduced to a low saturation and to about half the water content that the air could carry at that high temperature; that is termed 50 per cent relative humidity. All these rather complicated lines are simply saying that on the saturation curve, the 50 per cent curve is the line half way down, and the 20 per cent line is a fifth of the way up, etc.

I think that you now get a feel for how this works and how we might be able to use it. For a given body of air, the relative humidity depends on temperature and absolute humidity, but the moisture content does not. Once so much water has been boiled into the air, then it stays there unless it is physically removed in some way.

Let's take a practical example in buildings. The outside air in typical March conditions is about 5°C and 80 per cent relative humidity, and Figure 7 shows about 0.45 per cent of water vapour in it by weight. The air blows into a heated building through a window, increasing in temperature to 20°C. The moisture content stays the same; so the relative humidity has dropped from 80 per cent to 30 per cent. It's come from what looked pretty wet when it was outside to what looks pretty dry when it's inside. But things are going on inside. At the moment we're metabolising, and water vapour is rising into the air. So within the building, water vapour will be output. It may be from people, from the evaporation of damp or from cooking and washing and the drying of clothes. There will be a given mass transfer per unit time, and that will be carried away by a given ventilation per unit time plus absorption into the fabric.

Suppose that the room was heated by a coal fire and that the water vapour generated within the room output the moisture level by about 0.2 per cent, raising the relative humidity to 35 per cent or 40 per cent. The coal fire may change the air five or six times per hour. If, instead of a coal fire, the window is closed and central heating radiators used, the air will trickle in somehow. Then the air change rate might fall to about a sixth of the previous rate, causing one air change per hour. So the amount of water generated inside, which used to keep the relative humidity a bit dryish at 40 per cent, now puts in six times as much, taking the absolute humidity up to saturation - 1.6 per cent by weight. It's going to be getting pretty boggy and steamy. Somebody open a window!

This example shows that speaking about relative humidity without reference to temperature and about the influence of heating without reference to moisture generation or absorption or removal rates is meaningless. One of the important things about buildings is whether or not condensation occurs, and a useful concept is the dewpoint. Let's have a ventilation rate of two air changes per hour, taking the relative humidity up from 30 per cent to 65 per cent. If the air is then cooled down, we hit the saturation curve at 14°C, and the air has a dewpoint of about 15°C. The dewpoint is a useful proxy for the moisture content in the air. It is usually easier for people to understand the dewpoint temperature than a percentage. It also means that any surface in a room, such as a window surface, that is below that temperature will begin to have condensation on it. This has important implications for the behaviour of building materials.

PERMANENT RADICAL CHANGE
eg: different heating system
alteration of building
re-location of portable items

SHIFTING EQUILIBRIUM
eg: effect of progressive change

SPATIAL VARIATION
eg: Multi-occupied properties

CYCLIC FLUCTUATIONS
Particularly with air-conditioning

SEASONAL VARIATION
Particularly with constant temperatures

VIOLENT CHANGES
High occupancies
Equipment failure
Exposure to adjacent environments

Figure 8. Types of environmental change

I shall now look at several types of environmental change (Figure 8) to see what is happening to these variables within the building. The first is permanent radical change. Take a building which is falling into semi-disuse. You do something very different in it, causing a lot of things to move around. For instance, you might install a different heating system which reduces the ventilation rate since it is no longer being improved by the flue. You might put in insulation which reduces the temperature in the roof void and which might make it more prone to condensation. You might bring in catering activity which generates moisture. Many of the problems of excess moisture in the roof space of Clandon House were related to the National Trust installing a kitchen in the basement. Moisture went up a back staircase and transferred itself from this area over quite a long distance into another area.

So permanent changes may upset the system in unexpected ways. You insulate the room, seal the windows, change the heating, and gradually the balance tips over; the things which were more or less all right become slightly wrong. You often have positive feedback in building deterioration problems; if something becomes slightly wrong, the equilibrium is disturbed. The thermal conductivity in the area where condensation has occurred gets higher so that it loses heat even more rapidly, producing more condensation. Similarly, nasty bugs may start to grow and begin propagating, and if salts get into an area they attract further moisture. If you can keep it off the danger zone then all is well, but if it moves in for more than a short period, then the scales start to tip.

One finds spatial variation between parts of properties. People often control temperature and relative humidity very precisely in a showroom, but the moisture escapes into a building next door making it much damper than the one that is being controlled.

Changes may occur as cyclic fluctuations. Modern environmental controls tend to stop the internal environment moving seasonally, as it will tend to do with more natural processes.

One can use environmental systems to track the seasons rather than trying to create constant conditions where temperatures fluctuate round a mean. Sudden, violent changes can make things nasty for the building or for its contents. One jolt may be enough to seriously damage a museum or artifact preserved in an artificial environment. Alternatively, there are systems which give environmental changes in pulses, for example, with intermittent heating in churches. Normally the situation is stable, but when the heating operates, a pulse of heat is released into the building, which may move moisture from one place to another. Later on, there is another pulse; gradually a ratchet effect of pulses may occur leading to a final situation which is different from the original one and different from that which was monitored when the inspection was made. As we all know, nothing goes wrong when you inspect it; it always goes wrong in the middle of the night or at Christmas when you're not there.

Let's think about gradual change. I have recently been working on the evolution of lead covered roofs (Figure 9). Modern lead roofs are subject to corrosion on the under side, which is usually related to condensation underneath. Historically, there was a robust construction under the roof void: a bit of lead and some rough battens with gaps in between. Then the lead became thinner, the gaps closed up and plywood decks were introduced. In the last fifteen years, insulation was introduced. A roof enclosing a roof void or a room and the environment was shared between the room and the roofing material. When the battens were closed up and enlarged the lead became more isolated, and air, moisture and heat couldn't be transferred easily. A sheet deck is much more on its own: when the roof is warm, the lead is isolated from much of the room environment. When the sun falls on the south side of a roof with a roof void space underneath, it heats the roof. The void space and the north side of the roof also become warmer. The sun on the south side of the roof indirectly helps to dry out the north side. But if you get the second, more closed construction, each side of the roof is on its own! Whereas in the first case you can generalise about what is happening under the lead, in the second case you can't. This is just one example of a progressive change over history where the behaviour of a particular system has changed substantially.

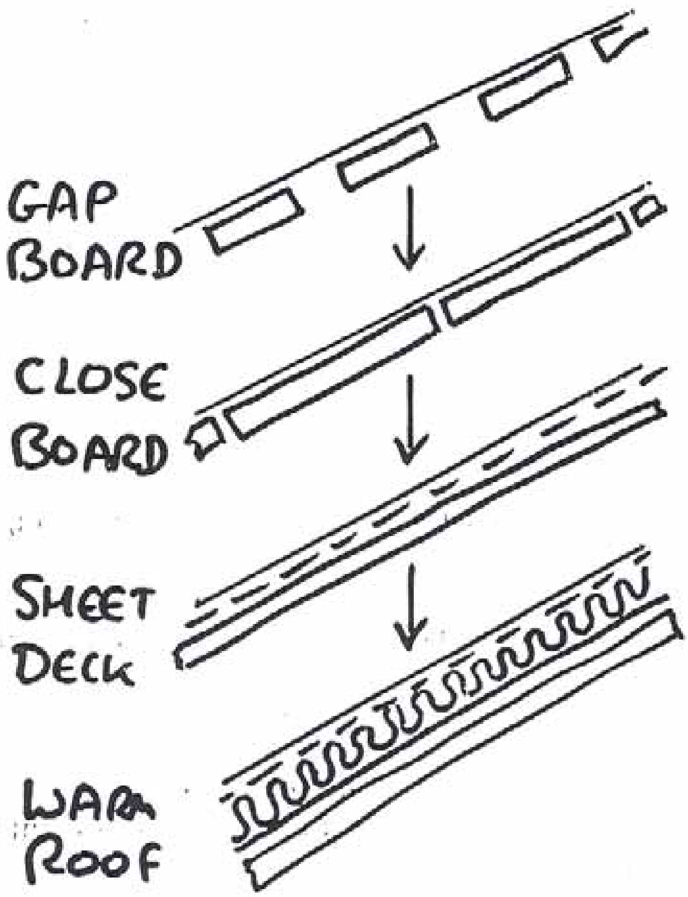

Figure 9. Evolution of the lead roof

If we then think about cyclic changes: consider the example of an art gallery where a spray humidifier system has been installed. The system controlling the relative humidity switches a humidifier on when the humidity is too low and switches it off again when it gets too high. The fluctuating humidity is measured by the response of a hair in a thermohygro graph (Figure 10). If an electronic sensor with fast responses is used, the changes are often far more violent than supposed: two or three times the average and pretty frightening! If the hair in the hygrograph is doing this, then so is the canvas on the back of the picture. Therefore, by trying to preserve these artifacts, one may be causing micro-fluctuation which will lead to detachment of the paint.

However, the room next door, which is not air conditioned has almost stable conditions with slow annual changes (Figure 11). Did we really have to spend all that money on an air conditioning system? People have put much effort into determining what the ideal relative humidity conditions are and then trying to maintain them by expensive to buy, expensive to run, difficult to maintain, fragile systems. I think that investigations should be directed much more into determining how much environmental abuse things can put up with before they begin to fall apart. So one's not saying, 'What is the ideal?'; one's saying, 'Where are the danger limits?' Would it be better to subject a picture to continual fluctuation as the control system 'hunts' around the optimum or to set some

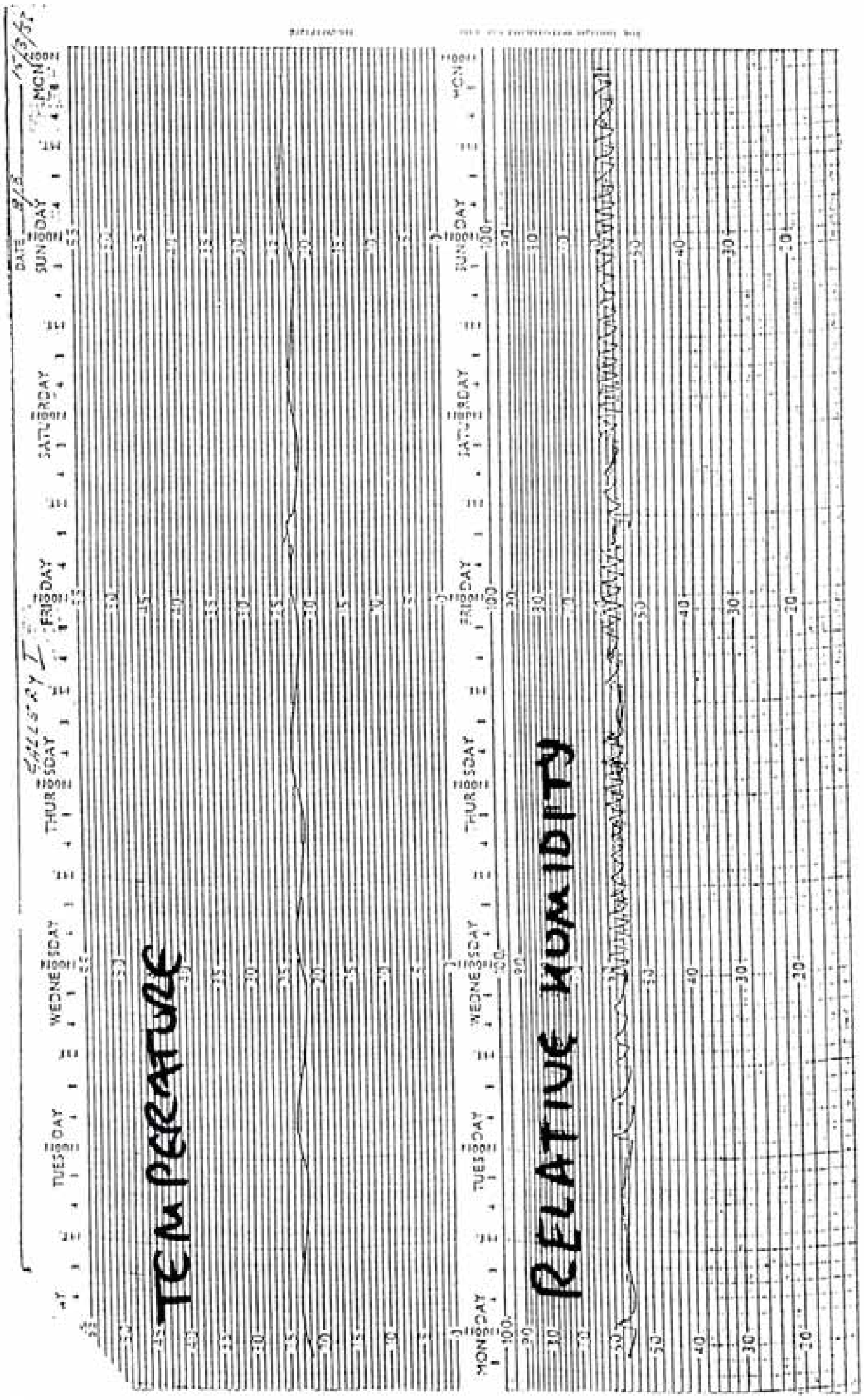

Figure 10. Cyclic changes in the temperature and relative humidity of art gallery

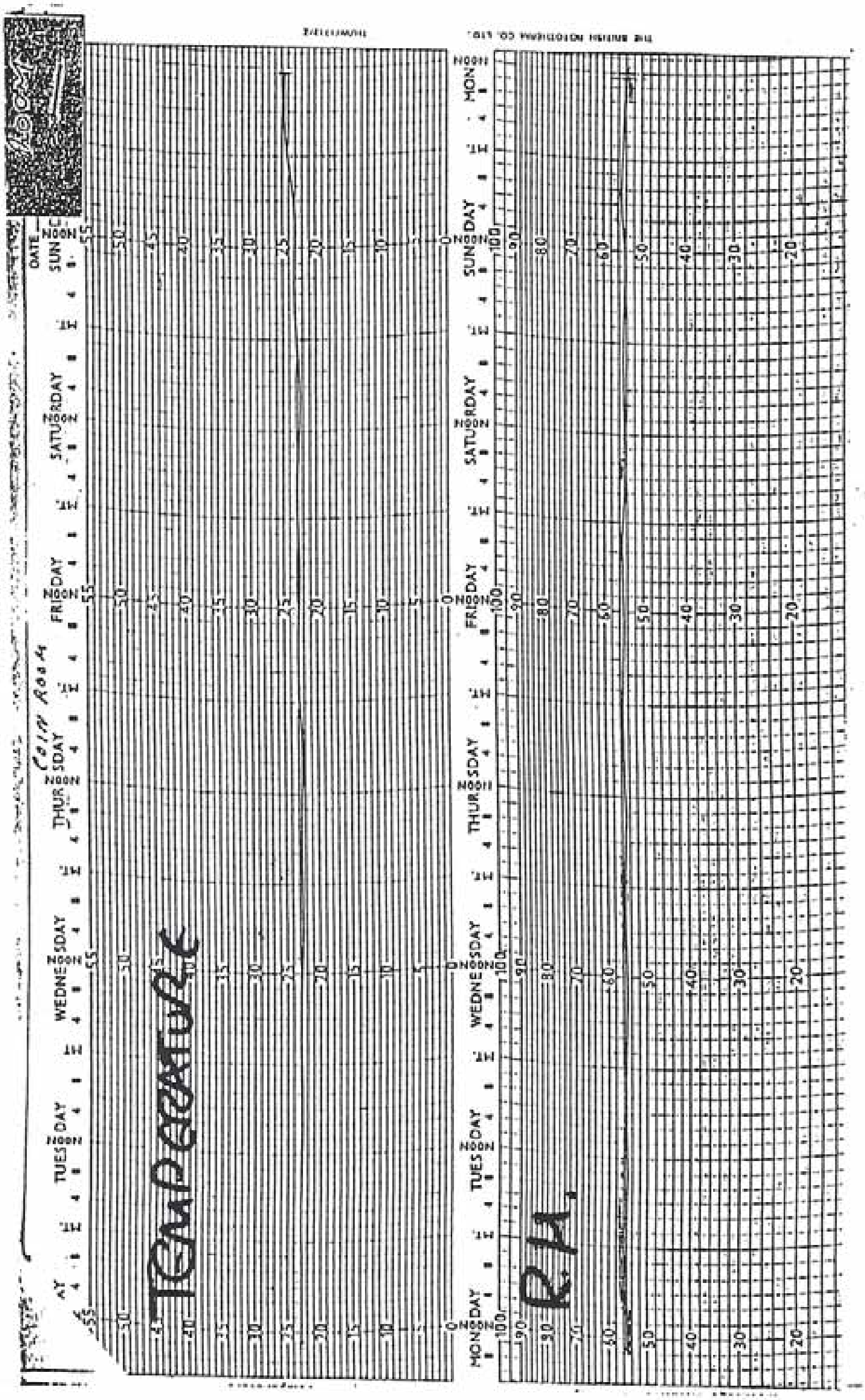

Figure 11. Cyclic changes in the temperature and relative humidity of a coin room next to an art gallery

margins on the relative humidity rate of change limits and then simply to take corrective action when those margins are reached?

We were involved some time ago with Lambeth Palace, which had an air conditioned muniments room with conditions similar to the example of the art gallery. They wanted a new air conditioning system, but we were not sure if they needed one, and so we did some monitoring. We found that letting things lie gave perfectly stable conditions but that sometimes the relative humidity went too high, and very occasionally it went too low. In the end, we threw away the air conditioning system and put in a fan which circulated the air. We put in a heater so that if the relative humidity got too high we could warm it up and pull it down. In case the relative humidity got too low, we put an alarm in so that somebody could find out what to do about it. A simple system with alarm limits in it may often be much better in the long run.

Buildings in which there is highly intermittent heating are interesting, for example, churches which are often heated internally for services. These days, the rural parson may have to deal with half a dozen churches which are only heated once a fortnight or once a month. Let's think of a church with traditional central heating radiators. In winter, it may get pretty cold or pretty humid while it's not occupied. Suppose that it goes up to 75 per cent relative humidity and 5°C. Then the vicar cycles round on Saturday to turn on the heating if there is going to be a service on Sunday evening. Gradually, the heating struggles away and perhaps raises the air temperature in the building to 16°C if you are lucky. One might have expected the relative humidity to drop back from 75 per cent to 40 per cent. Not much moisture will come into the space from metabolism, cooking or washing, but there will be evaporation from the fabric of the building. The vapour pressure increases, and the moisture content within the church might rise to 50 per cent but could reach as high as 70 per cent or so. If the radiators and heating pipes are on wet surfaces, which are wicks to indefinite reservoirs of rising damp behind, the relative humidity might go even higher. What is the result of this if you don't take account of dewpoints? Initially, the air wasn't saturated and the dewpoint was no higher than 5°C. At 75 per cent it would be under 2°C. So, no condensation would occur on any surface that was warmer than 2°C. When heating starts, it takes the relative humidity up to a say 60 per cent at 16°C. Condensation can now occur on surfaces which are colder than 10°C. A massive pile of masonry at a temperature of 5°C will not have all its surfaces up to 10°C within a day, and so a distillation process will result. The intermittent heating will kick moisture off some parts of the building, fetching it into the air so that it perhaps ends up somewhere else, for example in the roof or in an adjacent room.

Just to show you that I'm not talking complete nonsense, Figure 12 shows measurements at St John's in Stamford. The vicar comes in at about lunchtime on Saturday, turns up the thermostat to about 13°C and the temperature goes up and then starts to level off. He comes in on Sunday morning and turns the thermostat up as far as it will go, and the heat is on again. The relative humidity, which started off at about 80 per cent, coasts back down to 70 per cent, and the dewpoint comes up 5.5°C to nearly 11°C with this intermittent heating. Changes go on which don't feature much in the literature. But they may be extremely important when you start playing games with the building services and their controls.

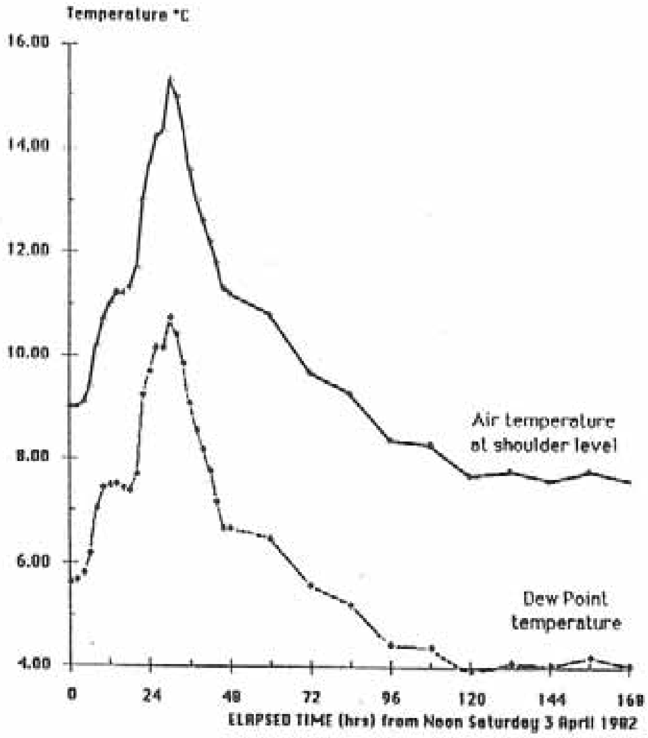

Figure 12. Radiator heating temperatures and dew point at Stamford St John

The opposite also occurs, for example in roof spaces. They can get very damp at times, but then when the sun comes out and bakes the timbers, it causes an enormous reservoir of additional moisture absorption capacity in the roof space because the timbers are dried out. This can help to reduce subsequent condensation.

Let us now look at a rather different form of heating: one which blows air into the church over a gas flame and heats it up, giving a fast response and a rapid drop in relative humidity (Figure 13A). Internal conditions give a violent response: the temperature goes whizzing up; the relative humidity goes whizzing down; the mean relative humidity is 60 per cent or so, but it would have been 70 per cent with the old system. The building would therefore appear to be drying out. After all, outside air is being brought in and never mind about the combustion moisture. If you look at what's going on, you find that the church is fairly stratified (Figure 13B). When the heating comes on, there's a rapid increase in the dewpoint which is due to combustion moisture. In these circumstances, when the heating starts to run and heats the air up, the fabric of the church gets left behind, and the increased moisture levels in the air can be accumulating within the fabric. Rapid temperature pulses and rapid relative humidity drops could be gradually sending shots of moisture into the fabric. The fabric is two metres thick in places, and so the problem might not be spotted for several years. So these are a few things that are going on under the non-steady state condition that is often obtained in real buildings.

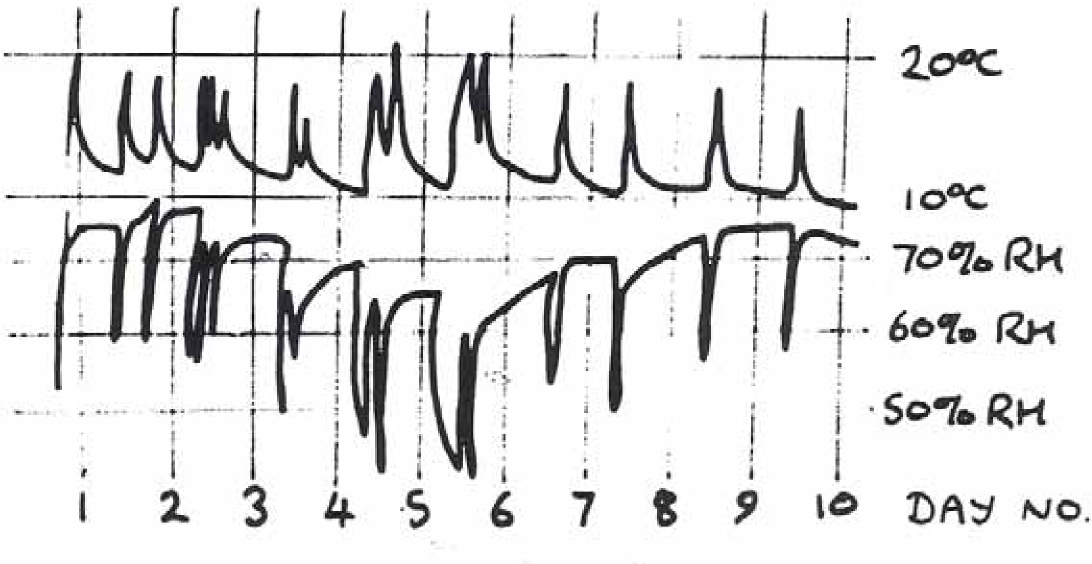

Figure 13A. Typical clerestory thermohygro graph (January 1986)

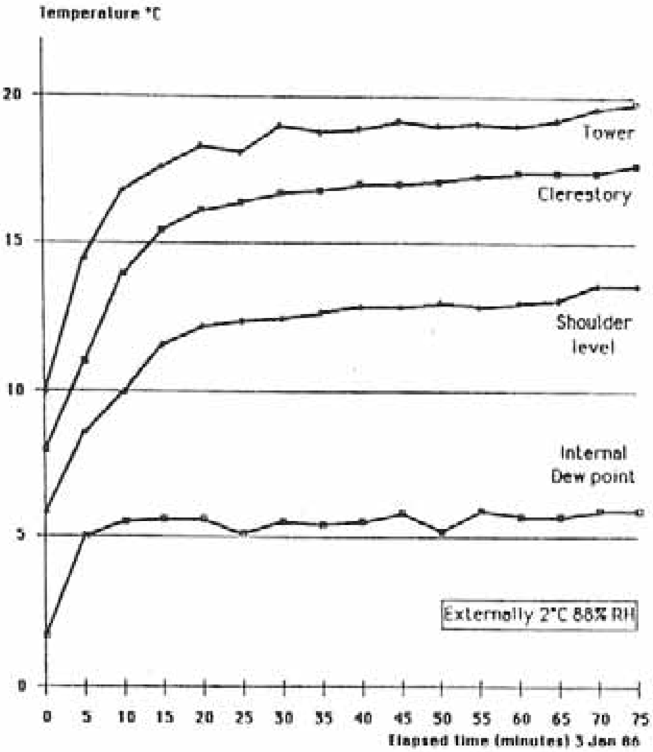

Figure 13B. Response to direct-fired air heating

Figure 14 shows the effects of seasonal change. The outside air temperature is lowest at about sunrise; when the sun comes out, it rises and then drops down again. The relative humidity varies within the range 80 per cent to 85 per cent, and the dewpoint is fairly stable because the amount of moisture in the air is similar, unless it rains or a warm/cold front comes along, or there is solar induced evaporation. In April, there is a much larger diurnal range because the solar intensity is much greater. The dewpoint will still go bumbling along with little change, and there is a greater range of relative humidity. In July, there is a similar but much higher dewpoint and the diurnal fluctuation is greater. Surprisingly, it tends to be a bit damper in the summer than in the winter in relation to relative humidity, absolute humidity or moisture content in the air. Since the air contains more moisture in the summer, it can be chilly in a massive building which lags behind the seasons. Therefore, quite a lot of moisture may be accumulated over the summer period and particularly over the early autumn.

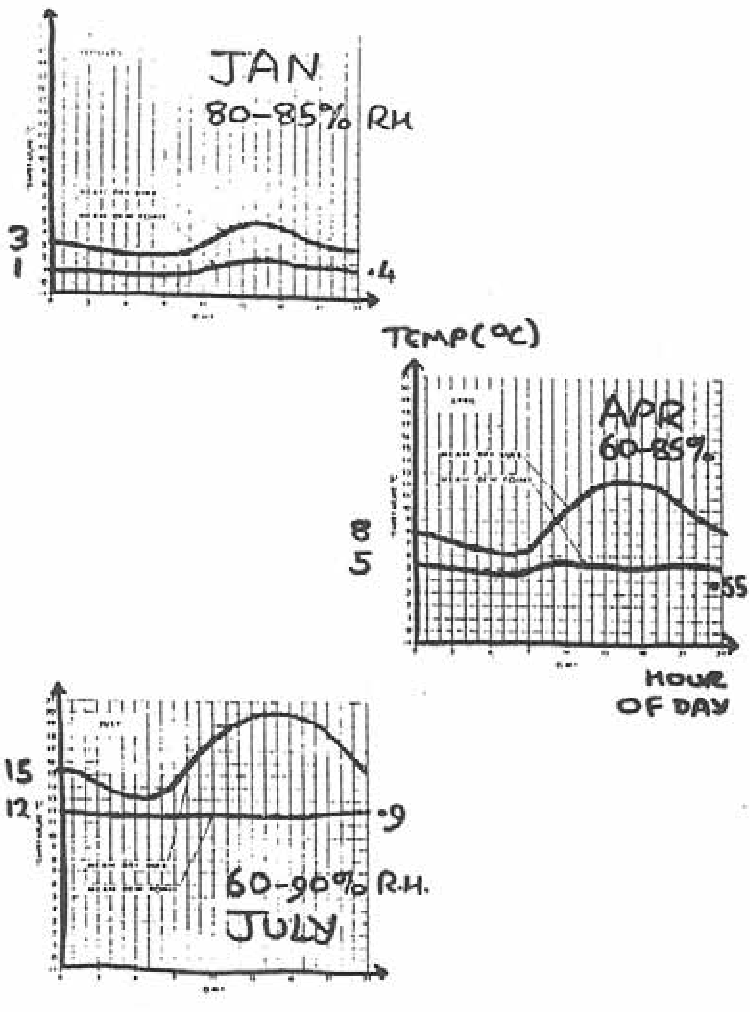

Figure 14. Mean figures for Kew (London)

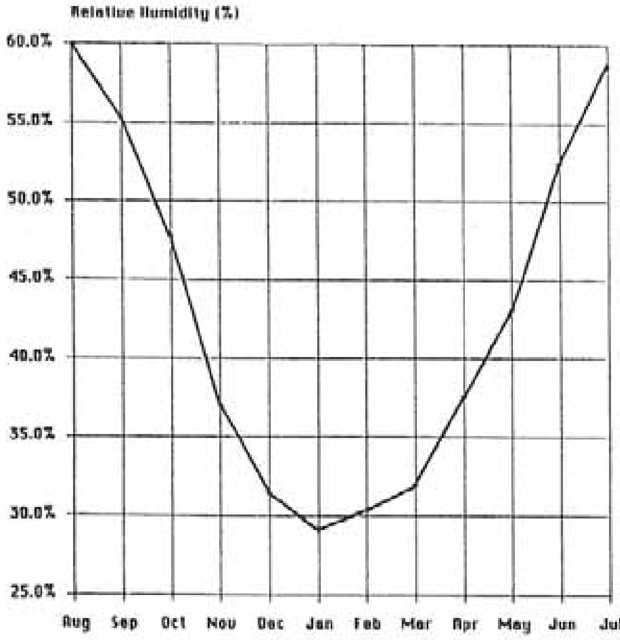

Figure 15. Resultant relative humidity in a dry building maintained at a constant 20°C (Heathrow weather data)

What does this mean for conditions within buildings? Let's start with the traditional heating regime. Take, for example, a room kept at constant temperature and ignore any internal moisture gain. What happens if external air is blown through it to heat it to a desired temperature? Figure 15 shows a curve of the London area at 20°C. Consider average monthly outside conditions in terms of temperature and dewpoint; the relative humidity starts at 60 per cent or so in August and dips to about 30 per cent in mid winter. Buildings can become rather dry if they have been heavily ventilated in the months of December to March. This was the traditional scene with central heating in old buildings where constant temperatures were suddenly coupled with large amounts of ventilation. If there were moisture gains within the building, then the relative humidity curves would move up a bit, but nevertheless things could become too dry in winter.

Suppose that we then say, 'Let's do it the other way and not manage this for comfort but for humidity stability within the building.' (Figure 16) The temperature required to maintain 50 per cent relative humidity starts off at 23°C in July and drops to about 12°C in the winter with no moisture gains. If there were moisture gains, a somewhat higher temperature would be needed in order to keep the relative humidity to around 50 per cent.

It is interesting that the difference between the external and internal curves is fairly constant. The difference sags a bit in the spring but otherwise it's typically 7°C to 9°C. So, a traditional building with an underpowered central heating system or coal fire which produced much ventilation and kept the radiant temperature up but the air temperature not terribly high would produce a mechanism for fairly constant relative humidity over the seasons. Modern environmental control mechanisms giving constant temperatures do not produce this.

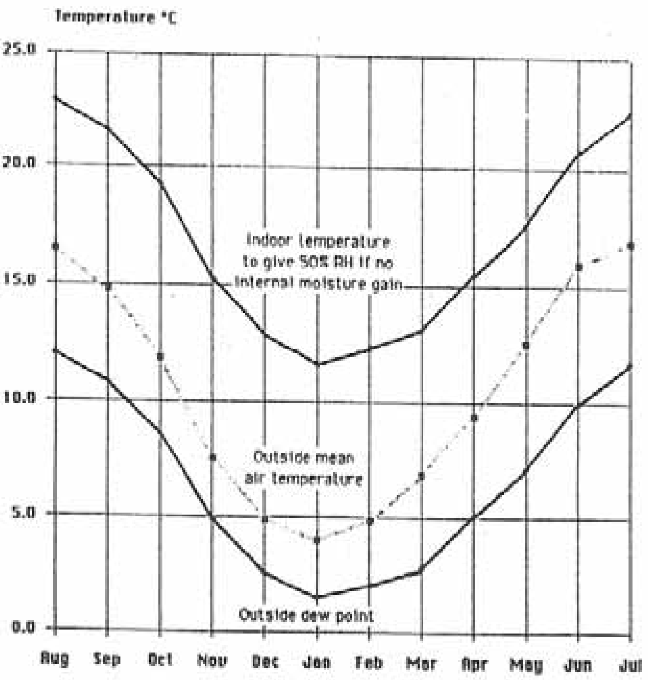

Figure 16. Average outside conditions and required indoor temperature to give 50 per cent relative humidity

This philosophy is beginning to be adopted by bodies like the National Trust, where the display rooms in their houses are often only open during the summer. They can let the temperature drift down in winter rather than using elaborate humidity control mechanisms. Some work on Calke Abbey has recently been written up.

Letting the environmental conditions flow rather then trying to maintain the temperature will often give a good result, as far as the health of the building goes. During August, September and October, in order to keep the relative humidity down, a higher than normal internal temperature of 20°C or so is required in the building. However, people often postpone putting the heating on as late as possible, sometimes until November, and the building becomes rather damp. When the heating comes on, there's a rapid rise in both temperature and the rate of evaporation from the fabric, which then becomes damp. You may find this in your own homes. So, if you delay in switching your central heating on until the last possible moment, for the first week or two after that condensation will appear on the windows at first, and then the whole thing will settle down. In many historic buildings and museums, I find that people subject their collections and buildings to similar environmental stress at the beginning of the heating season.

I shall finish with another cautionary tale from fully controlled environments. There is a reserve art gallery containing about £40 million worth of pictures and an air conditioning system. The humidifier stuck on the 5th and 6th of January 1984 (Figure 17), and this was repeated about once every three months. Of course, this always happens late on a Friday or at the weekend. The relative humidity is supposed to be 55 per cent plus or minus 5 per cent and suddenly reaches nearly 80 per cent. What is the point of air conditioning if it does that from time to time? For an extra £3000, sophisticated controls could be installed to

931/WTB
1 Feb 85

FIGURE 2
RESERVE GALLERY: HUMIDITY CONTROL FAILURE, 5-6 JAN 1984

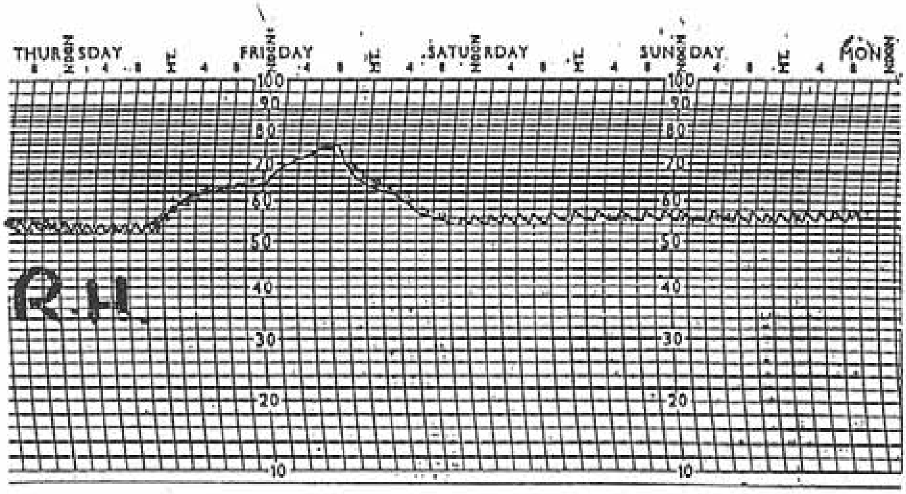

Figure 17. Reserve gallery: humidity control failure, 5-6 January 1984

set up safety limits which would sound the alarm and shut things off when it went past 60 per cent.

You don't only get these pulses with mechanical services. Figure 18 represents a National Trust house which has two rooms that are suffering the early autumn phenomenon in late September; they haven't switched the heating on, and the relative humidity has gone too high. But one room is fairly stable with a little increase in temperature in late afternoon when the sun comes out and a small increase in relative humidity due to evaporation from the fabric. The second room is adjacent to the restaurant, and there is a door between it and the display room which the custodians are instructed not to open to people. When it rains, they've got a kind heart, and so they let people through, and the humid air from the restaurant transfers across to the display room, upsetting the environmental conditions.

I hope that I've given a few indications of the funny ways in which environments can change within both new and historic buildings, both for expected and unexpected reasons. I hope that I've also explained the technique, that particularly relates to the psychrometric chart, of trying to track the heat and moisture right through the building and not just jumping to conclusions from on-the-spot measurements.

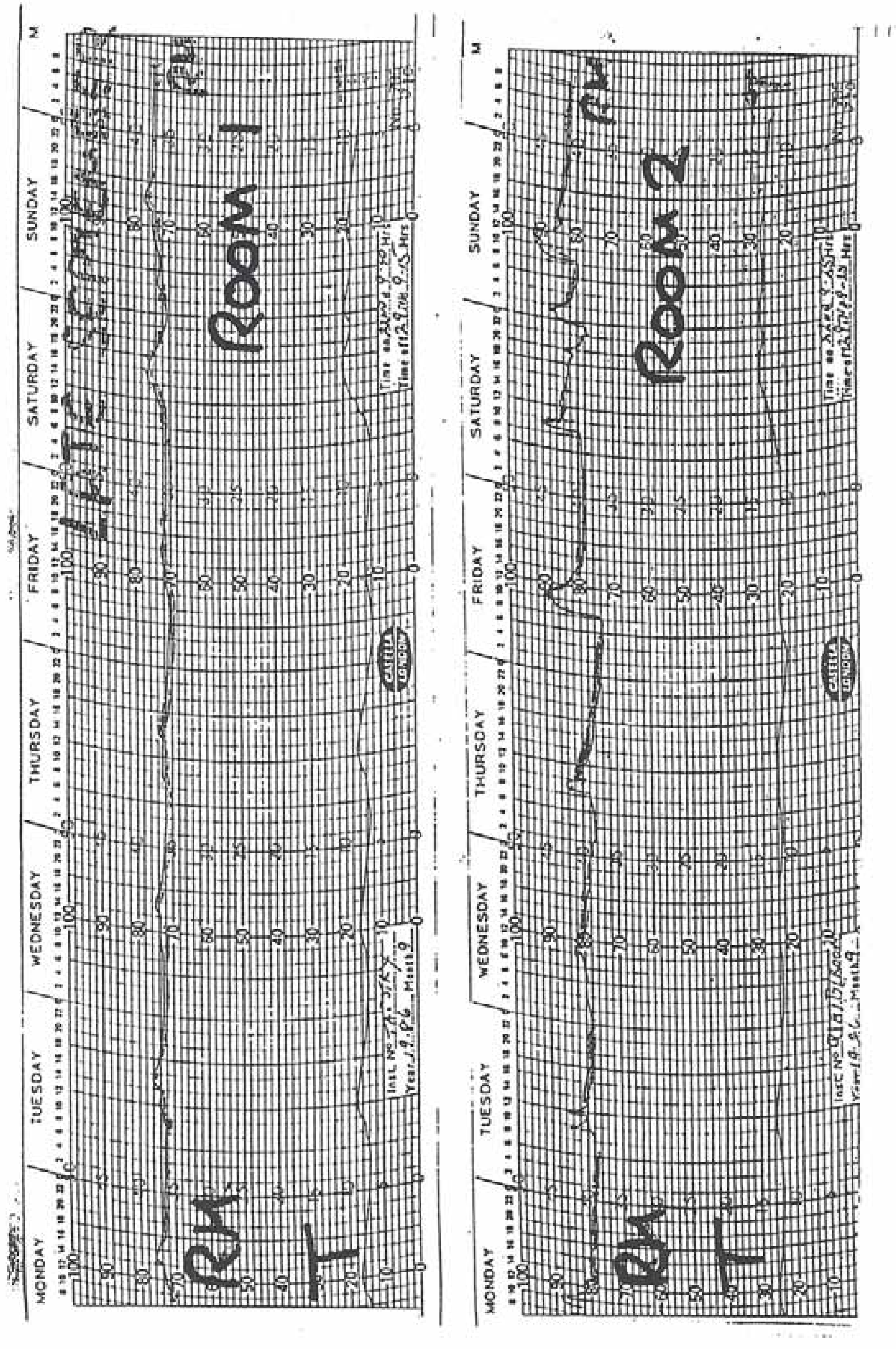

Figure 18. Late September readings from two rooms of a National Trust house

Discussion

Chairman
I shall use my position to ask the first question. Do you know how much work needs to be done to get from this powerful, structured, anecdotal evidence to an education program?

Bill Bordass
Not much, but it needs to be done and nobody seems to be interested in paying for it; most of the work which I showed you was done in spare time or on small budgets. For example, in one project for the Church, a weather station could not be afforded since it would cost the whole budget for the project. So external temperatures and relative humidities plus information from the Met Office were used to infer what was going on outside. Rainfall is important, since when it falls on a lead roof, it cools it rapidly and leads to condensation underneath. The wind direction is also important. The building in question was a church with a uniform internal cell which had major temperature gradients within it, making it necessary to log the temperatures at many positions. It had nine separate roof spaces. The interactions between the internal environment and the roof space environment were highly dependent on which way the wind was blowing, and if this wasn't monitored, it was difficult to extract the noise from the signal in the roof spaces. I also mentioned that the sun beating down on top of the roof space environment had a much greater effect than anything else. It was heating it up and drying it out so that it transferred moisture. The sun rose on the east side, gradually becoming more intense and heating the east side up so that moisture came off into the air. For a while, that condensed on the west side. Later on, the whole temperature of the air space increased. By the end of the day, the west side had dried out well. There were nine monitoring points both within the church and outside and one device under the roof space. About one hundred monitors would have been necessary to characterise the system fully. These needed to be within the individual environment and also within the fabric. Many things occur on almost geological time periods. You can't tell by taking a spot measurement and can't always tell by taking a season's measurement, but must persevere with perhaps not many sensors. Suppose that this year the average moisture content in August is 13 per cent; next year it is 14 per cent and the following year it is 15 per cent. Now, is that a ratchet effect or is it because the summer was colder?

Chairman
At the moment, is the information in the hands of a limited number of experts?

Bill Bordass
I am not sure if they have the information or only bits of it. The more that I find out about systems, the less information there is in order to give answers to the questions which people are asking. I don't think that there is much to do, but it has to be consistently carried out in some detail over a period of years.

Chairman
So we therefore still have to get the information?

Bill Bordass
Yes.

May Cassar
You mentioned that buildings and their contents could withstand a degree of fluctuation. How can we establish how much relative humidity and temperature fluctuation a painting can withstand before it gets damaged?

Chairman
This is non-destructive testing as opposed to the alternative.

Bill Bordass
There are two experimental systems for many of these things. There is the real system where conditions aren't ideal. So, let's put some tags on that to find out what's going on. In one church that I looked at, all seemed fine until after the summer of 1986, when there were signs of more efflorescence on the walls. This was probably caused by a miserable early part of the year, followed by a hot July and August. Moisture had accumulated in the fabric over the cold March, April and May and then was blasted through the south face by the sun. But alternatively, a change in the heating system might have accumulated more moisture in the fabric which was increasing the efflorescence; it had nothing to do with the sun - I just happened to notice it after the summer! If one had put some stereographic photography onto that efflorescence, one would have been able to measure whether there had been any more of it. Equally, you can do the same on pictures: there are many non-destructive ways in which you can look at the surface, such as time lapse photography over a very long period, photographing it once a quarter or doing some short term photography when the air conditioning system is stressing. There are lots of ways in which you can look into what's happening to real artifacts in real conditions without putting them under any additional stress.

Then there are laboratory proxies. You can start preparing materials by popping them in test bags and seeing what happens. We already have enough laboratories in terms of completed buildings provided that people are willing to give access to the building and to finance the research and provided that they don't want quick results. It's a question not of setting up systems to study, but of collecting information which is already there. If only you could measure that.

May Cassar
The technique which you described for measuring the changes and fluctuation of a canopy or painting still means that you are subjecting a particular painting to fluctuations, and so you are contemplating sacrificing it.

Bill Bordass
Yes, I am saying don't sacrifice a painting (unless it's one with no artistic merit); observe a painting which is already being subjected to changing conditions. Find out whether the cycle of fluctuations is damaging.

May Cassar
I don't think that the period of time or the rate at which it happens can be easily identified.

Bill Bordass
These are just the things that we need to look at. Some things happen so slowly that the system tolerates them, and other things happen so fast that the system won't notice them; but how are these quantified?

May Cassar
So stability is what we ought to be aiming for?

Bill Bordass
Yes. Then you have the basis of a good argument. For example, if there is a short term fluctuation over two hours, then the time constant in many systems will be so large that it's been and gone before they've responded. Other systems might be just the other way. If it's got beyond that, you can set up a fairly simple programmable electronic monitor which can flash up a red light when it has

happened. But we don't have these things, particularly for buildings. It either looks all right or it doesn't, and there aren't many techniques that say, 'I'm not quite sure about that; let's stick one of those in and come back five years later.' There's plenty of material in historic churches for example. Now if somebody in a dodgy position would say, 'I'll put that monitor there', then maybe five years later is enough. If not, somebody could go back one year later, and rather than just making a physical inspection, they would have some understanding of where the danger limits were. But we don't have that.

Jagjit Singh
It is difficult to achieve control of environmental conditions within the roof space. For example, in an uninsulated roof, the warm air will go up, and when it meets the cold air in the roof space it will condense. Subsequently, the moisture of timbers will rise, encouraging insect infestation. Would you like to comment on this?

Bill Bordass
You'll have to be more rigorous in what you are saying because heat rising and meeting cold air isn't how condensation occurs. Condensation would occur if warmer air was carrying moisture up and had the heat removed when it was up there. Cold air will both remove the heat and carry away the moisture; the result will depend on the balance between cooling and dilution effects. Environmental management has potential because the traditional way of keeping roof void spaces healthy, for instance, has been by having good cross ventilation 365 days a year. There was usually a thin roof finish without many membranes which meant that air could go through it. But if you put more insulation underneath, even if it is entirely sealed off from a building to prevent moisture escaping, you will still get situations where condensation occurs. This happens particularly during October and November, when there are fairly high outdoor absolute humidities, and there is the 'start of the heating season' effect discussed earlier. There are also clear skies at night and the roofs get cold. Now if under that sort of situation there is copious ventilation to the airspace, then the roof will accumulate more moisture than if it only had a small amount of ventilation. The next morning, when the sun comes out and beats down on the roof, the best thing which you can do is to ventilate in order to clear that moisture out. One can get a long way by ventilation management. For example, you might be doing it in relation to the temperature and the timber moisture content or in relation to some sort of differential sensor between inside and outside conditions. You'd say, 'The outside is benign at the moment; let it in', or, 'The outside is hostile at the moment; keep it out.' I think that much can be done very cheaply with a sort of pocket calculator technology. Once the model is calibrated, one can get much better performances from passive or semi-passive systems for controlling environments in buildings than we have to date. Certainly in the last half century it's got worse because there are fewer people poking around buildings tuning them up. I think that if we could re-calibrate the science, it would then be fairly easy to develop the technology to at least make the most of the ambient resources that are available to us. But we may not be able to get down to a 12 per cent level. It might be a question of keeping it off 18 per cent or something. I think one can't be rigorous about these levels. It's a question of statistics, and saying, 'If it's here, one has a pretty good chance about it being robust, and if it's there, one has a pretty good chance of it being unreliable.' So let's keep it out of the unreliable range and push it into the robust range. But we can't always be in the ideal position, or we're spending too much.

Bob Hayes
I'd just like to go back to the specialist education. It would be a pity if, after these three days, we had to back off introducing specifications for the control of moisture levels because we were concerned that a little learning might be a

dangerous thing. We might have to turn it round and say that what we seem to need to re-learn are the things which were always known about buildings, in the same way that Mrs Beaton knew about household work. The learning for buildings is what we've been forgetting. A lot of the important lessons are basic and simple: understanding what happens to moisture in buildings. This can be taught since we have the information. In particular situations it gets extremely complicated, and to get the full story in a particular building you may need to monitor it very thoroughly. But that doesn't mean that we should stop educating or re-educating. It's a point which I'm quite worried about.

Bill Bordass
I fully agree with that. The basic knowledge is easy enough to understand. Advancing the practical application in detail does need some research. It's no good jumping to conclusions about it; one must have a better knowledge base.

Bob Hayes
We are monitoring temperature and humidity in 60 houses together with Data Loggers for the National Trust. Information now goes back for three or four years; so there is a large volume of data which I'm sure the National Trust would be happy to make available for analysis.

Bill Bordass
Have you correlated that with other environmental variables, for example, timber moisture content, etc?

Bob Hayes
Not directly. I agree that there is poor coordination and a great deal of work that should be done, but there is a large volume of data being collected by ourselves and others.

Chairman
There is real danger in teaching the young by means of failure. Sorry to put it in such a hard way. If you say to them that these are the principles involved in moisture transfer and that this is what's happening if you get it wrong, there is much evidence to suggest that it isn't an effective way of teaching people. It just frightens them because at that stage in their education, they're trying to learn all sorts of other things such as that it is necessary to have the staircase in the same place on the ground floor as it is on the first floor. This takes about two years. How do you get from structured anecdotal evidence on failures to positive advice on what to do?

Steve Curwell
That problem's been solved for structural designers, for example. You can't design a building to fall down. You can only design it to stand up.

Chairman
Oh yes - no problem with structures, but it was interesting that the two speakers that we had this afternoon didn't concentrate on successes and said, 'What a wonderful way of doing things.' They showed a whole history of disasters, and therefore I wondered if this was the state of educational knowledge.

Bill Bordass
Some of the things which I showed you were not disasters because there was no direct evidence that those situations that had disaster potential precipitated disasters. It was worrying that they might have done and that they were so far removed from the theoretically ideal situation. Corrective 'good' theory and practice might even be attacking the problem from the wrong end with the best being the enemy of the good rather than acceptable conditions being the aim.

Chairman
Yesterday I gave a lecture to some of my masters students on a similar area, and one chap came up to me afterwards (he's a very nice student) and said, 'The problem is, if I'm having a dream and I dream of ending up like you, I know I'm having a nightmare. That's not how I want to live my life. What I want to dream about is being like Richard Rogers.' It's getting our knowledge round to that sort of positive, exciting and interesting way perhaps.

Tim Hutton
Dr Bordass' masterly exposition of the curve, the complexities of the sources and the fates of moisture in a building rather begged a question in my mind as to what's happening to the other vapours within the building structure, which we are only just beginning to think about. I think for example of formaldehyde, solvent vapours and some of the other chemicals. This particularly brings to mind a case involving a fiendishly complex substance that we were dealing with a year ago: creosote, which isn't just one vapour. It is a lethal substance with at least 100 components. Not only do you get cycles of evaporation and condensation, but as it condenses and re-evaporates and distills, it undergoes a process of fractional distillation; the substance itself is changing throughout the process. Some of these substances have significant but poorly understood toxicities as they become more concentrated or pure. I think that this has implications for what some of the other speakers may be talking about tomorrow or the next day. I don't know what thoughts you have on that?

Chairman
That's a nice bit of 'partial pressure': partial baked theory.

Tim Hutton
They are also solvents. Organic solvents not only sink in water porous substances, but dissolve in what you would regard as impervious materials such as plastics or the organic material of paints and fabric furnishings, etc.

Bill Bordass
Moisture illustrates the whole building dynamic, and it's important to get a hold on that because there are sources and sinks and plugholes and all sorts of other things going on which all apply; we need at least two talks which concentrate on that. Sometimes problems get too complicated. People frequently complain that clients aren't sophisticated enough to understand, to maintain or to operate services. You can take the exact contrary view of the clients saying, 'These things are too complicated; I do not need that; I cannot afford to spend on this sort of operation.' We can't always rely on Hutton + Rostron to tell us to stop using pesticides and fungicides. One must try to reduce the problems to a level where they can be coped with using simple management processes rather than by hyping the problem up so that it needs much more sophisticated management. There are many ways at the moment of complicating the problem. Our efforts should therefore be directed at trying to find simple ways out.

Chairman
It was always argued that proof of the divine origin of the Church lay in the existence of the clergy. If the Church hadn't a divine origin, the clergy would have ruined it long ago. A bit of that argument applies in that we have an enormous building stock, which has survived the professions and the experts for a long time. So maybe all is not lost. It's the same point that you are making: it's easy to make problems.

Geoffrey Hutton
I agree with Bill's approach: architects love problems to solve but we should really be avoiding them. That applies very much to buildings; you shouldn't use

things which then create problems which you have to solve. The traditional building incorporated much law which was learnt by rote. Our present dilemma in education is that we don't fully understand the basis of the traditional law. Now the problem is that we have to re-learn, in possibly a scientific way, why buildings work and why some traditional buildings appear to have been successful. Bill's idea about buildings being a laboratory is significant. It does appear that one is investigating failure, but failure is one extreme of success. Failure is the other end of success on a continuum. It is difficult to investigate success because unless you monitor a building, you won't know if it's successful. For instance, you mentioned Clandon Park. Don't say this building is wrong, but just log it every half an hour for eighteen months to find out what's happening. I agree that the National Trust is tackling too many problems in too many different places. I would much rather see it take one building, bug it thoroughly, understand the mechanisms there and use that to interpret other buildings. One needs consistent data. For instance, we had an automatic weather station at Clandon, and we were able to cope with what was happening within the building. That's why we could track down the problem in the basement: anybody who pours twenty gallons of boiling water on a quarry tile floor at three o'clock every afternoon is silly.

Bob Hayes
But you point that problem at us. The National Trust is investigating 100 or more of its houses and coming up with problems and solving them. So I agree that it would be very good to be able to thoroughly instrument one building and find out everything about it. But you probably will not discover everything about the other buildings. The other problem is that it can't all wait. If environmental controls have to be made, they must be made as quickly as possible. We must move forward on many fronts and coordinate the information that comes in.

Geoffrey Hutton
Yes, I agree.

Chairman
I'm sure that's right. I was climbing around in the top of St George's Chapel, Windsor about nine months ago, and I came upon the maintenance instructions signed by a gentleman who called himself C Wren. The instructions were to sweep the vault and its top every week and to look for cracks and damp. That had been followed for 300 years. I foolishly pointed out this piece of parchment. The result was that it was taken away and put in a museum and not replaced with anything.

Nick Pillans
I would like to open up an aspect which no one has touched upon so far: the increasing need for sound insulation in the building envelope in order to achieve large degrees of acoustic separation between the inside and the outside. Many local authorities are taking this seriously with regard to aircraft and traffic noise. It seems that many things, particularly the effects of sick buildings, are pointing us further in the direction of open buildings that are more in tune with the outside environment. But a strong rule is being insisted on by planning authorities under the instructions of environmental health officers: to virtually have a hermetic seal on a lightweight building structure. They want to maximise the insulation, and now we're in the situation where architects must fine tune their insulation carefully to meet the requirements of local authorities. This is something that's pulling us back the other way. It obviously has a positive effect on the sick building syndrome in that if you reduce the stress of noise and the high frequencies that come through certain types of construction, a better internal environment results. But at the same time, it gives us the problem of how to maintain the contents of

the environment. I don't have a solution, but I think that someone should pull us away from water, which we've been obsessed with all afternoon.

Bill Bordass

The first thing, which I am sure that Pat would endorse, is that there aren't sick buildings; there are bad buildings. There are ways of doing things that don't rely on any specific system if they are done well. People seem to be more tolerant of environments where they can do things. If a sealed building is needed to counteract noise, that doesn't necessarily mean that the individual can't decide to have the noise and to open up the building on occasions if he or she prefers. One problem is restriction of choice because once you've got a mechanical system, it's cheaper to have a sealed window than it is to have an openable one. The removal of the openable window is often the last straw. If you have a system which isn't much good and you lack the openable window which gives more choice, then you are more likely to be in trouble. So I would avoid single solutions as far as possible and install things that give the users flexibility to control the variables that seem critical to them.

Hanne Weiss Lindencrona

I'm an architect from Sweden, where we are more concerned with people's health than with the pictures' health. So I don't mean to be rude, but humidity is not fundamental in our discussion. The speech was interesting, and it was very good for me to hear because in Sweden buildings are very technical. Mechanical ventilation is introduced almost everywhere. With respect to noise problems, we feel that we are fighting a heating and ventilating 'mafia'. You also argue that you want to be more flexible and not to have the most elaborate or sophisticated systems. You want something that is reasonable in the buying of, the maintaining of and the managing of. Have you had any problem with your ventilation 'mafia'? Also, when you talk about building samples, it seems that you are more interested in digging into troubles than in showing what is good. And it is easier to say what is bad than what is good.

Chairman

That's a defect in our national characteristic. It's always best to come in a good second than to win.

Hanne Weiss Lindencrona

But who will stand up and say what is good? How do you measure when you are looking at people, not structures?

Bill Bordass

In a world of specialists you do need a generalist, and that isn't working as well as it might in relation to buildings. The architect used to be the generalist, but somehow the architectural profession hasn't tackled the problem of being a generalist. In a more sophisticated world, you need different types of architects. They still try to be the whole man but they can't be; nobody is.

Moving on to the ventilation 'mafia'; there always seems to be a contradiction between energy efficiency, which is, 'Batten down the hatches' and everthing else which says, 'The more air the better', unless it's horrible polluted air from outside or unless there's a humidity control problem. A measured amount of air may be required, and one is still struggling with that problem. The solutions, I've discovered, tend to be in practice. I have done some scientific analysis on things which allow some choice of system. So you can have controlled mechanical ventilation plus opening windows. Simple systems tend to be more robust even though you're paying for two systems. Both together need not be as expensive as one system which is perfect. Not long ago, nobody thought in terms of people's health in buildings or of anything save the ventilation requirements of the people in relation to the amount of air which they needed to breathe and a certain amount to dilute smells. If they were smoking or doing other noxious things, then you had to take account of that. It's increasingly apparent now that all this furniture and flooring is giving up stuff which we don't like. The air conditioning can put in about half as many nasties as it removes; so we need about twice as much air to get back to balance. I certainly feel that natural systems give plenty of scope because how else can you get ten air changes per hour through a room without vast mechanical devices? Yet you can by throwing a couple of windows open. So they allow flexibility and management, but they are by no means a universal solution.

Peter Fitzsimons
I'd like to ask you a question on behalf of the little man. Many of the things that we've been talking about involve a fair amount of research and expenditure of hardware. I go out to churches around the country, small and large, where the first thing that I'm always told is: 'We haven't got much money to spend on this sort of thing.' I wonder if, given the amount of money that it takes to research a particular problem in a particular building and design an appropriate solution, the best advice to give to the vicar in those situations might be to sell his central heating system and to use the money to give every member of his flock a greatcoat and a hot water bottle.

Bill Bordass
I said that in a talk about church heating ten years ago, but I also added a drop of brandy. There are lateral solutions to certain problems. If we're making things too complicated then we've got the wrong end of the stick. One must do some detailed research to define the problems. It costs money to buy a box of instrumentation which is often less powerful than a pocket calculator that costs £5. It's all a question of volumes and markets and there are fundamental principles which we have lost sight of. We have too large a portfolio of goodies which we can apply, and there are too many complexities that arise. You can cut through much of that with a knife and say, 'Look, here is a simple principle which it's sensible to strive towards.' Now, in practice you are not going to be able to apply those in a pure and simple form, but as you move away from them you go past warning triangles and things saying, 'Think about this' and 'Think about that.' On the other hand, it is possible to develop simple instrumentation on the lines of smoke detectors. Once set up in a church in a specific area of the building which is prone to problems, they will tag an environment. Once you have confidence in the theory and have invested enough money, the cost of instrumentation by volume and technology will be reduced. You can come up with very simple solutions and that is certainly my ambition. One has got to go over the complication 'hump'. It is no good not understanding and coming up with part solutions that don't work. One has to find ways of making it simple. I have a vision that something could be made available to inspecting architects that was tied in to the local university or polytechnic, who could analyse it in a standard way. Then you could suddenly increase the power and value of something that is being done anyway using potentially low cost technology. If you are not prepared to pay for the development cycle, then you are not going to get there.

Chairman
I must admit that I always get quite annoyed with places where I'm expected to cope with a hundred years of neglect by reducing my fees. This is a very unreasonable approach to be adopted. There is something quite fundamental to be argued there: buildings are a cost that must be paid for, and there's no use in trying to fiddle the books.

Aino Nevalinen
I work at the Department of Environmental Hygiene; so my point of view is one of

health. I would like to comment on the ventilation 'mafia' which is quite familiar in our country too. I feel sorry for the ventilation engineers because they have been doing their best, and they have tried to find us the right systems. Then we also have another 'mafia' in Finland: the health 'mafia'. A group of people have decided that the reason for all these indoor air problems is mechanical indoor ventilation, but it isn't as simple as that; there are also chemicals and such things. In a northern climate where the temperature gradient in winter is about 60°C when it is -30°C outside and 20°C inside, is it possible to get a constant relative humidity inside?

Bill Bordass
No.

Mike Hardy
I'm one of the ventilation mafia. I think that Scandinavia is in many ways in advance of us. I am thinking particularly of the 1988 Healthy Indoor Air Conference in Stockholm. Have you applied any of your research to light structures and structures which have high internal heat gain, such as the majority of office blocks in London? Although I can see it working in traditional buildings, there are likely to be problems when it is applied to office blocks.

Bill Bordass
The problems of moisture related deterioration in office blocks are rather different from those in historic buildings. Environmental problems are usually less of a problem in an office because the relative humidity is unlikely to be terribly high. Moisture related problems are likely to occur due to straight forward building defects of some kind. Office buildings are fairly tolerant to even cold bridging. I have just been involved in a very large study of how much energy is used in modern offices. One of the things to come out of that study is that heat gains in offices are nothing like what people say they are, and people have been putting in unnecessary air conditioning systems. There has been scope for studies in this country. If they manage their heat producing equipment, having a fully air conditioned building, they could drop back to maybe 20 per cent of the area air conditioned, and the rest of the area will manage without. It is easy to look at the worst case and to say, 'I'm going to have to design a massive system to cope with all the possible outputs everywhere.' If you could define the problem more precisely and enter into a sympathetic discussion between the designer, the manager and the user of the building, then there would often be more flexible and possibly humane solutions than the conventional kind of engineering solution.

Chairman
Well ladies and gentlemen, we have had a very interesting afternoon, and it must be clear to all of you who didn't know it before that there are some very real problems around. Whereas it could well be argued that we understand the principles behind those problems and therefore the principles behind possible solutions, there is certainly not sufficient knowledge available on practicable and workable solutions. It seems to me, therefore, that there is a great need for evaluation. We need to be evaluating over our wide range of buildings what's happening, and it's no use leaving all that to the poor old ventilation engineers. They are doing their best, but it is too big a problem. I think that two things are necessary; if you really believe that this is a serious issue, then you must have an evaluation programme. Certainly you must link it to the modern building stock because that's where the majority of the interest is. If you could link it to the modern housing programme then there's a chance of work getting done. So it's got to be linked to a modern-day large research and development programme. There is a massive research and development programme into the management of buildings to be announced by the Government. In fact there are two programmes; they are called 'Link Programmes'. One is to do with air quality and

health, and one is to do with operation and management programmes. The first one is going to be announced tomorrow at the Queen Elizabeth Hall and the second one is going to be announced in a fortnight's time. They are programmes of research which will put a great amount of money into this very area where academics and people in the real world can get together and do something about it.

Evaluation is the way forward, and it must be linked to big fat chunks of our building stock and to big government funding. As long as you pretend that it is a special problem that relates to a minor part of the building stock, then there is no hope other than blaming it all on one or two people who look after the stock and who are trying to do their best. That is the first part. The second part is that we also need a focus for this knowledge, and at the moment I don't think that there is one. We need a focus whereby the results are turned into practicable solutions. As a result of the availability of such solutions and such documentations, a proper educational programme of whatever kind and in whatever places can be developed.

I'm leaving you with those thoughts to discuss over the next two days. I would finally like to ask you to join with me in thanking our two excellent speakers for this afternoon and for producing a most interesting discussion.