Where the greatest benefit can be derived is in the use of database driven software. Whilst comments have been made about the nature of the databases used, nonetheless the facility to reduce data input and to merge information between, for instance, a lighting program and a load calculation program can be very useful. Our view is that the next few years will be marked by further development of this type of software before dynamic modelling becomes the really useful tool we all hope it will be.

References

1 Holmes M.J. Computers, Engineers and Thermal Loads *Microcomputer Newsletter No 5*. Building Services Research and Information Association. April 1983.
2 *Proc. Dynamic Thermal Modelling Workshop unpublished.* Building Services Research and Information Association. October 1985.

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7 Lloyd's of London

Introduction: *C.T. Barker*

In this century Lloyd's have twice outgrown buildings that they had commissioned to accommodate the insurance market and associated facilities. In 1977, they asked six leading international architects to present a solution which would allow the insurance market to be efficiently housed, but at the same time allow for approximately 200% further expansion. The result of this competition is the new Lloyd's building, designed by Richard Rogers and Partners, with Ove Arup the engineers for the building services and structure.

Concept

The building consists of a rectangular block, containing an atrium, and surrounded by six satellite towers. A two-storey basement occupies the entire site. As a general principle, the main building above street level contains underwriting and office space, the satellites – vertical circulation both for people and building systems, and the basements – plant and service activities.

The most important single aspect of the design is the need for adaptability. By concentrating lifts, stairs, service risers, toilets etc in the satellites and supporting the building on external columns, the floor space within the columns is entirely unobstructed and restrictions on use are minimised. The Atrium, in addition to providing a source of daylight to the core, enables the insurance markets which are located around it to operate visually as one market, a requirement that has always been important to Lloyd's.

General description — building

The main building is a rectangular block, 68.4m × 46.8m. The lower ground floor is set slightly below street level and contains public areas, a restaurant, and the reinstated old library. The floor above this, together with the first four floors (galleries) around the Atrium are the Room, i.e. the insurance market. At the beginning of the design, only one floor plus one gallery constituted the Room, but market growth in the last six years has resulted in 100% additional space requirement. In the design the market can expand up to and including Gallery 6. Other floors not used for underwriting will be used for offices, with the exception of Galleries 11 and 12, which contain the Committee and Executive Suites. This includes the Committee Room, which has been adapted from the original Adam Great Room at Bowood House, Wiltshire.

In order that the single space Room can be achieved, the underwriting galleries open directly onto the Atrium, the other galleries are glazed.

The first six galleries form a complete ring around the Atrium, but above that the galleries are cut back to suit the rights of light of adjacent buildings.

Each floor division consists of a number of horizontal zones.

1. The beam grid.
2. A high level services zone which contains lighting extract air, smoke detection, sprinklers.
3. A steel panel which sits on stub columns at the beam intersections and acts as permanent form-work, supports acoustic panels, and provides a services support grid.
4. A concrete floor which provides a fire barrier and supports a computer floor.
5. The low level services zone which contains the supply air, the local heat pumps, condensing water distribution, and in underwriting areas additionally chilled water distribution, electrical power, data and telecommunications systems.
6. The raised floor which is a modular panel system, incorporating air inlet grilles and flow outlet boxes for electrics.

The zoning of the floor is fundamental to the concept of an adaptable space.

1. The services can be re-routed easily and are not constrained by vertical structure.

2. All services associated with a zone are contained within that zone and can therefore be modified without disrupting other tenants. In this context it is worth noting that Lloyd's expect up to 2,500 individual tenancy agreements in the building.
3. False ceilings are eliminated, access to services is via the 600 × 600 floor tile or removal of light fitting, which is designed to facilitate this.
4. Partitions are suspended from the bottom beam grid and can be installed, mostly without effecting other elements. Closures either for fire or acoustic reasons around the services above the beam grid are achieved by a prefabricated dry construction gasket type closure.
5. In the raised floor zone, smoke separation is achieved by dwarf walls on a 200m^2 grid. Tests demonstrated that no acoustic separation in the floor zone was required.

The external cladding consists of triple-glazing units arranged on a modular basis. The outer slab comprises a standard double glazed unit, incorporating reflective glass as one skin. The second pane being a specially rolled glass with concave dimples to give the glass light reflective properties at night. The third inner pane is openable for cleaning purposes and return air from the light fittings is drawn through this space, offsetting the heating and cooling load of the building resulting from the highly glazed architectural solution.

Satellite towers

There are two main types of satellite tower. Satellites 1, 3 and 5 are principle personnel circulation towers. They are essentially all the same, and consist of a lobby, four high speed external passenger lifts, a fire escape stair, prefabricated toilet module and a service riser.

The remaining three are principally fire fighting satellites and include the Section 20 requirements for enclosed fireman's lifts, dry risers etc., in addition to being the principle electrical risers for the building.

The satellites also form the support structure for the air handling plant rooms which are located on top of them, and as support structures for the vertical ductwork distribution systems which are located externally to the building and serve the floors above street level.

Basement

The light service areas for the lower part of the building, such as kitchens, toilets, maintenance are located in the upper basement, while the heating services, central refrigeration, boiler plant, thermal storage, basement air-handling, substations, diesel generation and no-break plant etc., is contained at the lowest level. In addition, the main stores are in the lower basement, and because of traffic restrictions in the surrounding narrow streets, two hydraulic vehicle lifts of 10 and 24 tonnes are provided so that delivery vehicles can be brought into the basement for unloading.

Central energy plant

To minimise building energy consumption, chilled water heat reclaim coils are located in all the building exhaust ventilation systems. Chilled water is circulated back to the central chilling plant where this low grade energy is rejected and upgraded via an auxiliary condenser into the building heating system. In this mode of operation the central chilling plant is, in effect, being used as an electrically driven heat pump.

The central plant comprises two 1500kW screw compressor machines, fitted with double bundle condensers and one 1200kW standard machine. Detailed analysis of the building thermal performance indicated that 1500kW of building cooling load was available at all times and that up to 3000kW was available from cooling and reclaim sources that could be usefully re-used for building heating.

As the maximum demand for heat by the building does not co-incide with the maximum available reclaimed heat from the chillers, the 400m^2 sprinkler storage tanks are used as thermal reservoirs. The circuitry allows the chillers to reject heat into the tanks while there is little or no load requirement in the heating circuit. Likewise it allows energy to be drawn from the storage tanks when the chilling plant is inoperative.

General

The building is unusual in that it combines a number of features which together have created a challenging and complex problem, and have resulted in a response which it is hoped will provide a satisfactory working environment for Lloyd's which satisfy their requirements for change and at the same time contribute to the architectural stock of the city.

Among the many criteria which have figured, some of the more important to the services design have been the high population densities in the market areas, the need to change from an office to an insurance function with minimum building disruption, the galleries opening directly onto the Atrium, energy conservation, the uptake of information technology in the City and the architectural demands on the engineering systems. The following sections take some of these elements and elaborate on them.

The architecture of air conditioning: *Graham Anthony*

During the last decade we have been witnessing a significant change in architectural thought. The doctrines of the Modern Movement, which have so forcibly shaped our environment for the past fifty years, are no longer considered inviolate and the rigid adherence to functionalism has been replaced by a less dogmatic attitude. The emergence of the *Post-Modernists*, with their language of allusion and metaphor, has irrevocably blurred the architectural image.

Architectural movements are, of course, complex affairs, part stylistic and part ideological; however, their development often reflects the social and artistic values of society and to this extent change must be partly attributable to society's disapprobation with modern architecture. Modern architecture, devoid of gratuitous decoration, relies on the formal expression of function to achieve modelling and scale. Failure to achieve this is best exemplified in the design of the modern office block, which with its emphasis on maximum rentable area and floor upon floor of identical space, leaves little scope for the formal expression of its components. The developers and their architects, motivated primarily by large profits, have systematically demolished many fine buildings in the inner cities and replaced them with banal, featureless blocks. The confidence of the public in the architect's ability to provide better buildings than the traditional ones he has sought to replace is understandably lacking. Hence the increasing strength of the Conservationist movement and its success in preventing much modern architecture from being built.

The new Lloyd's of London building is firmly rooted in the concepts of the Modern Movement. Born of ideas current in the 1960s, it has attempted to distinguish between those elements that have a limited life span and are therefore disposable from those which constitute the main building fabric and are thus permanent. It has been designed as a free standing office block hemmed in by the existing fabric of the City. Built of concrete, glass and stainless steel, its main rectangular form encompasses an Atrium extending some 80 metres high, culminating in a semi-circular glazed barrel vault. Six satellite service towers positioned around the periphery of the site are joined to the main building by glazed links. Like much of Richard Roger's work, it invokes a passionate response, mixed, in about equal measure, between enthusiastic acclaim and critical dislike.

The architectural philosophy behind Lloyd's is essentially one of Expressionism. The aim, to provide legibility of the component parts, thereby establishing their inter-relationships, and to juxtaposition them so that they form a sculptural entity. The overlayering of elements and the attention to detail of each component becomes the method by which the grain and scale of the building is defined. Historically, in classical architecture for instance, this would have been achieved by the use of motifs within the forms of the cornice, pediment and pilaster.

In the design of this building the formal expression of the service elements is as important as that of the more traditional ones, such as structure and glazing. Consequently, they become part of the initial design equation and not relegated to a secondary role — to be positioned where possible after the major decisions of structure and envelope have been made.

If all services are to be exposed, it follows that they need to be co-ordinated and positioned with the same degree of care as the rest of the building. All decisions, whether large or small are therefore made from both an aesthetic as well as a functional standpoint and often only after extensive drawing and modelling has been done. This inevitably increases the design, detailing and drawing programmes. To achieve this it is necessary to strengthen the relationship between the members of the design team, particularly the services consultant and the architect. It changes established roles and requires new approaches from both sides towards their respective disciplines. Compromise is inevitable. However, both parties have to have a much more flexible attitude towards solutions, sometimes abandoning traditional roles for the more innovative. The base line, is of course, the point at which each discipline knows he has taken the other to the limit. To fully understand this game of bluff and counter-bluff, knowing that the function has not been seriously impaired by considerations of aesthetics and vice versa, it is necessary for both parties to involve themselves in the understanding of each other's work and decisions have to be reached in the full knowledge of this higher order of things.

In the same way as structure can be formally expressed allowing an appreciation of the way the forces are structurally resolved, so the movement of large volumes of air in an air conditioning system can be expressed by exposing ductwork with the same degree of clarity as one might expose structural beams and columns. It therefore becomes possible with only a very limited knowledge of services to comprehend the basic rationale behind the heating and ventilation distribution system of this building by observing the various services elements and the ductwork configuration.

The six satellite towers house the main forms of vertical distribution, both for people and services. Four of these terminate in three storey plant rooms, each floor delineated by a break in the external cladding. They serve Gallery 1 upwards and their size is conditioned by the need for separate plant to service tenanted and underwriting floors as well as provision for Lloyd's to expand their underwriting activities up to Gallery 6 in the future. The remainder of the air handling units serving the two basement levels, lower ground floor and the main underwriting space known as the *Room* are situated in the lower basement, together with the major items of plant such as the chillers, boilers and generators etc.

From each of the satellite plant rooms the supply (one for underwriting and one for tenanted office) and one extract duct emerge to bend and descend vertically at the end of the lift lobby. For those familiar with the building there is a certain irony here. The glazing to the main building is predominantly obscure except for clear vision panels at either standing or sitting height depending on floor usage. The ends of the lift lobbies, are however, totally glazed with toughened clear glass, in some instances offering exceptional views over the City. It is, of course, beyond this glazing that the three large ducts descend, albeit reducing in size as they feed the lower galleries. At each gallery level a supply and extract branch duct passes through the lift lobby to re-emerge externally in a complex interchange and distribute horizontally along the facade, with stab-offs periodically occurring along the run to penetrate the external cladding at raised floor level. In detailing terms it was necessary to design a language of support structures for the ductwork to take into account the permutations of size and configuration. In conjunction with this, the actual construction of the ductwork, insulation and overcladding had to be considered. It was decided at an early stage not to pursue the concept of a waterproof cladding system similar to that of *Centre Pompidou* but to provide stainless steel overcladding which offered protection from water but was not intended to be either water or vapour proof. The eventual specification was Rockwool insulation sealed with a polymeric vapour seal. In addition a sacrificial layer of foilbacked Rockwool was used to prevent the rivets securing the rigidised stainless steel overcladding from penetrating the vapour barrier.

One of the implications of designing an external ductwork system was that it became a structural element which had to satisfy the District Surveyor. There are no Codes of Practice covering this aspect of the design and there was little data available on the structural performance of very thin tubes; none was found for spiral wound tubes. Before structural design started, load tests were carried out on some sample sections of ductwork in order to check the model of behaviour. The final designs were validated by constructing full size mock-ups of a number of typical conditions and loading them to working load, design load with its factor of safety and ultimately destruction.

Although not apparent from the road, the external services at roof level are both complex and dramatic. At Gallery 13, the basic rectangular shape of the building has been cut back by terracing at Galleries 7 and 10 to leave a U-shaped roof around the glazed atrium which projects a further storey before terminating in a barrel vault.

The basic design of the roofscape revolved around the organisation of two main elements. Firstly, the Cooling Towers and secondly the Atrium ductwork. The latter pulling large volumes of warm air from the upper reaches of the atrium and passing it through heat exchangers before discharging it to the atmosphere.

The position of the Cooling Towers was primarily governed by structural considerations as their weight had to be transmitted to the perimeter and atrium columns. Depending on the size and complexity of their supporting structure, there was some degree of flexibility in positioning them. The main concern, however, was the visual effect of the towers through the glazed north end of the Atrium. To lessen their apparent solidity, it was decided to opt for a circular form rather than the conventional square one. Three forced draught towers gave the best ratio of height to diameter and these were placed in line at the end of the Atrium.

Each extract duct positioned at high level on either side of the Atrium required a fan and heat exchanger, which, due to their weight, had to be supported from the roof slab. The ductwork, however, nearly three metres in diameter and supported from the Atrium columns on steel cantilevered brackets, needed to turn back on itself in order to connect up with the fan transformation piece. This visual effect of these large ducts projecting beyond the Atrium like vast trombones is astonishing. To achieve this it was necessary for the ductwork bend to be cantilevered as well, the joint to the transformation piece being a flexible connection and therefore non load-bearing.

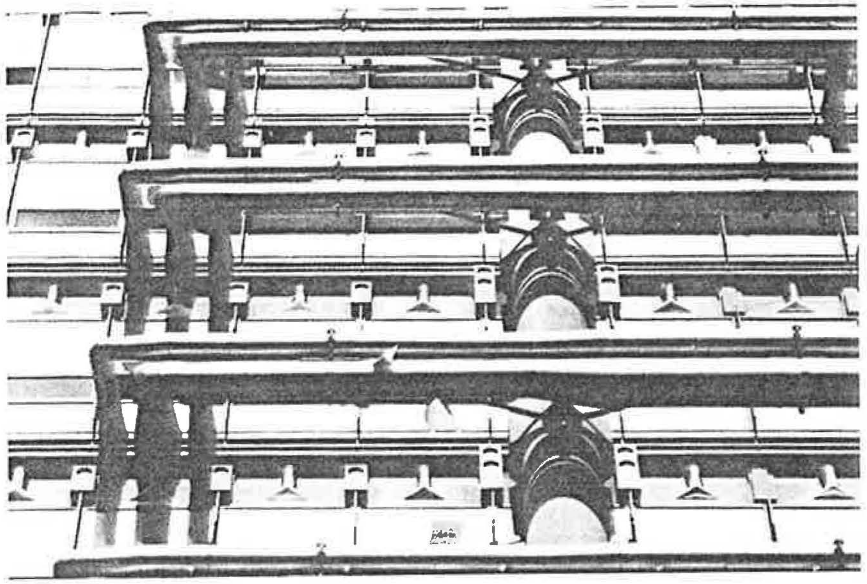


Figure 7.1 *External horizontal ductwork feeding raised floors*

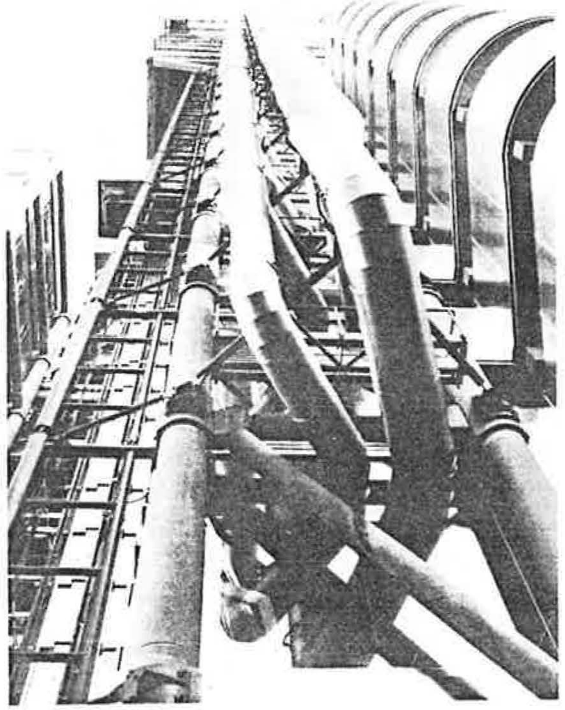


Figure 7.2 *Vertical ductwork descending from plantrooms*

Figure 7.3 *View of Lloyd's redevelopment*

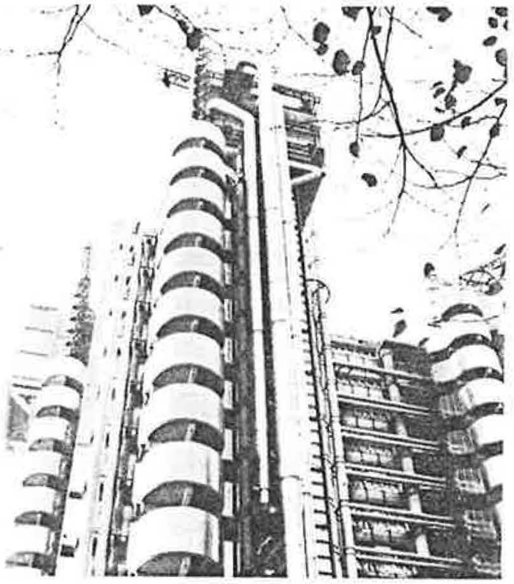
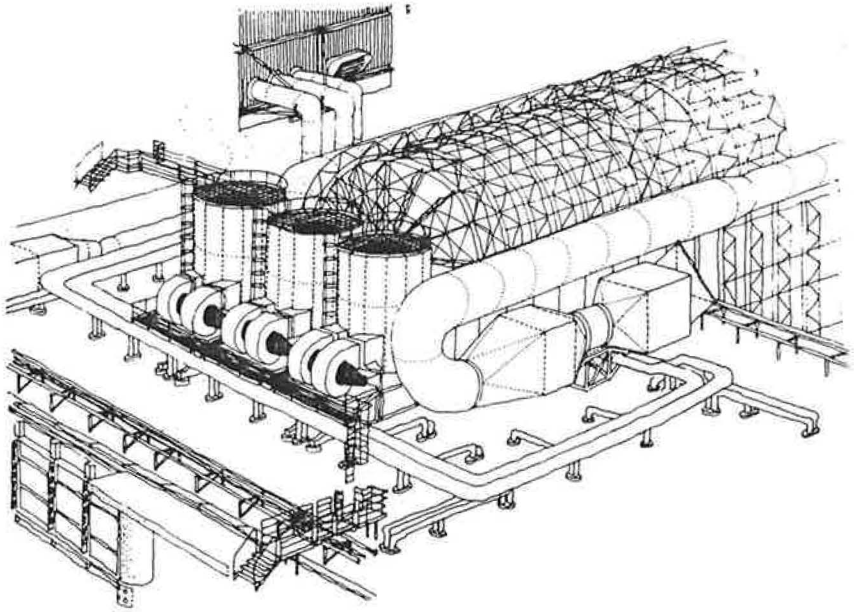


Figure 7.4 *Design sketch of roofscape*



Primarily, because of the visual impact of the ductwork, it is perhaps possible to overlook the fact that the air conditioning is only a part of a fully integrated exposed servicing approach, which includes pipework and electrics, both internally and externally. This in turn must be seen within the context of the expression of all other major elements from staircases, toilet capsules, wall climber lifts to cleaning cradles at roof level. Thus it can be seen that the expression of air conditioning cannot be separated from that of the other elements but must, therefore, be part of the overall approach to architecture.

Prediction of the environment inside a 13 storey atrium: *Richard Waters*

The central area of the Lloyd's building forms an atrium, thirteen storeys high and 11 × 33m in plan. The lower three galleries of the building and the ground level form the insurance market area and are open directly on to the atrium. The remaining galleries are separated from the atrium by glass. The barred roof and the south elevation of the atrium from the seventh to twelfth galleries are completely glazed and in contact with the outside environment. A schematic view of the atrium is shown in Figure 7.5.

We were concerned that on a winter's day cold downdraughts, from the high level glazing in contact with the outside environment would cause discomfort to staff working on the atrium floor. Hand calculations and then more complicated computer analyses were used to make approximate assessments of the effects of cold downdraughts. The results from these calculations and the conclusions drawn from them are reported in this section.

Hand calculations

For a cold downdraught inside the atrium to occur two conditions must be met. The air must come into contact with cold surfaces and there must be enough power available to drive air re-circulation within the atrium. The first condition is satisfied by the large area of glass at the top of the atrium in contact with the cold air outside the building. Our calculations indicate that on a cold winter's day around 200W are available to drive the circulation of air at high level. This power estimate assumes that 0.1% of the energy loss at the top of the atrium is available to drive air

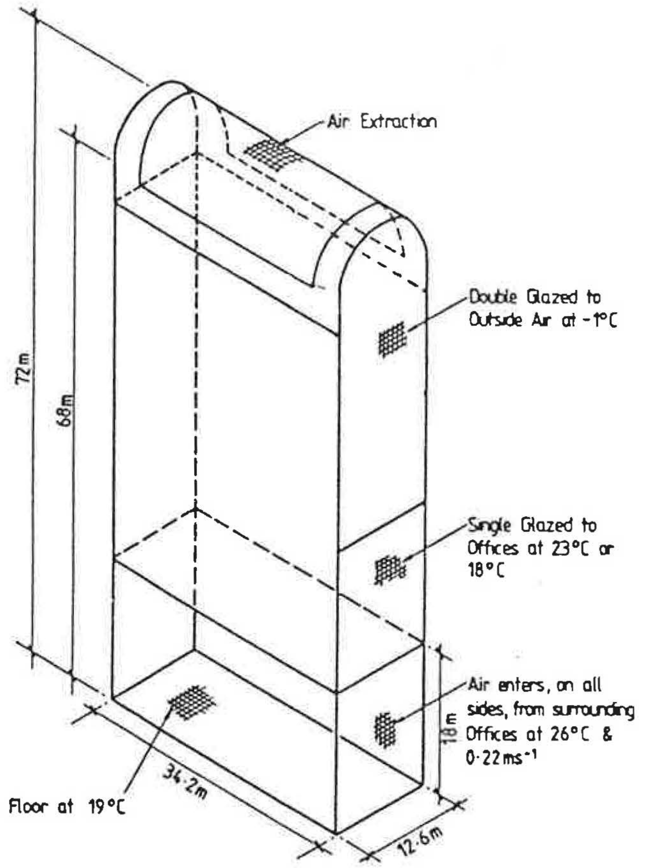


Figure 7.5 *Isometric view of atrium*

circulation — the conversion factor was found in Tritton's (1) book on Physical Fluid Dynamics.

The atrium's external glazing stops at the seventh floor of the building. There are then three sealed floors, galleries 6 to 4. Our calculations indicate heat conducted into the atrium space from these levels will slow but not stop downdraughts.

The bottom three galleries plus the ground level of the building open directly onto the atrium. This area will become the underwriting room. We estimate that the air from these levels has a speed of about 0.5 to 1.0 m/s as it rounds the corner from the ceiling of the underwriting room into the atrium. It is likely that this will be sufficient to break up the cold downdraught.

The peak motion of air above the seventh storey in the atrium was estimated from the thickness and velocity relationships for buoyancy driven flow over a flat plate. Velocity (V) and thickness relationships of the type:

$$\delta = x\ (Gr)^{-m}$$

$$V = \frac{v}{x}\ (Gr)^{n}$$

were used with m and n taking the values prescribed by Tritton (1). Assuming temperature differences of the order 10–20°C between the glass surface temperature of mean internal air temperature it was estimated that the maximum air velocity would be some 1.5m/s; and that a typical length scale for the width of fluid would be approximately 2–3m.

Computer analyses

The purpose of these analyses was to re-examine the air flow inside the atrium with a different type of calculation technique, and thus qualitatively check the values and effects predicted by our hand calculations.

It was decided to use a fluid dynamics field modelling technique to understand the effects of cold downdraughts within the atrium. A literature survey showed that only a few field modelling techniques were capable of simulating flows at the high Rayleigh Numbers found in this atrium. A field modelling technique produced by Prof D.B. Spalding (2) selected for this study. One of the major reasons for this selection was the work by Markatos and Pericleous (3) subsequently published, on laminar and turbulent convection in an enclosed cavity. These workers obtained converged results at Rayleigh Numbers ranging from 10^{3}–10^{16}. The predicted results were in good agreement with well known correlations up to Rayleigh numbers of 10^{8}, and appeared to extend the validity of these correlation up to Ra of 10^{13}.

For a two dimensional flow situation the fluid dynamic equations are:

1 *Continuity* $\frac{\delta(pV)}{\delta y} + \frac{\delta(pW)}{\delta z} = 0$

2 *Horizontal-direction momentum* $\frac{\delta(pVW)}{\delta z} + \frac{\delta(pVV)}{\delta y} = \frac{\delta}{\delta z}\left(\mu\frac{\delta V}{\delta y}\right)$

$$+ \frac{\delta}{\delta y}\left(\mu\frac{\delta V}{\delta y}\right) + S_{v}$$

3 *Vertical-direction momentum* $\frac{\delta(\mathrm{pWW})}{\delta z} + \frac{\delta(\mathrm{pVW})}{\delta y} = \frac{\delta}{\delta z}\left(\mu \frac{\delta W}{\delta y}\right)$

$+ \frac{\delta}{\delta y}\left(\mu \frac{\delta W}{\delta y}\right) + S_w$

4 *Scalars* $\frac{\delta(\mathrm{pW}\phi)}{\delta z} + \frac{\delta(\mathrm{pV}\phi)}{\delta y} = \frac{\delta}{\delta z}\left(\Gamma_{\circ} \frac{\delta \phi}{\delta z}\right) + \frac{\delta}{\delta y}\left(\Gamma_{\phi} \frac{\delta \phi}{\delta y}\right) + S_{\phi}$

Where

$$S_v = \frac{\delta}{\delta z}\left(\mu \frac{\delta W}{\delta y}\right) + \frac{\delta}{\delta y}\left(\mu \frac{\delta V}{\delta y}\right) - \frac{\delta p}{\delta y}$$

$$S_w = \frac{\delta}{\delta z}\left(\mu \frac{\delta W}{\delta z}\right) + \frac{\delta}{\delta y}\left(\mu \frac{\delta V}{\delta y}\right) - \frac{\delta p}{\delta z} + \mathrm{pg}\frac{\theta}{T_0}$$

These equations represent the steady state turbulent flow of air.

Turbulance effects were allowed for by using a two-equation turbulence model that solved for turbulent kinetic energy and dissipation. In addition to this buoyancy generated turbulence was allowed for by following the practice recommended by Rodi(4).

The field model solves the partial differential equation for continuity, momentum and turbulence in the following manner. The equations are reduced to algebraic relationships by integrating over an elemental volume and using upwind differencing to represent the convective terms. Pressure predictions are obtained from a pressure correction relationship which works on the principle that the correction is sufficient to produce velocity changes that satisfy continuity. The SIMPLEST practice was used to solve the resultant algebraic equations.

We decided to estimate air movement and temperature distribution in a series of two dimensional slices in the atrium. A three dimensional model was not used, because we were not concerned with the exact topology of the air movements, but with creating a mathematical analogy of our hand calculations.

Several simulations of slices were carried out. We varied the assumed internal glass temperatures with the intent of estimating their effect on air movement. External air temperature was taken as − 1°C. Air from the office abutting the atrium, at galleries one to three was allowed to escape into the atrium and was extracted at high level.

Sample results for a slice 34m wide are shown in Figure 7.6. The slice represents the situation corresponding to offices up to the sixth gallery and the twelfth on alternate sides of the atrium. In this simulation the results were characterised by a single re-circulation loop extending from the top of the atrium to about the fifth gallery. This loop has a slow moving central region; and fast moving edges where air speeds of up to 1 m/s occur. This flow pattern matches the results of our hand calculations. The computer predictions show the downdraught being predominantly destroyed at low level in the atrium by the effect of heat transfer and conditioned air from the offices abutting the atrium.

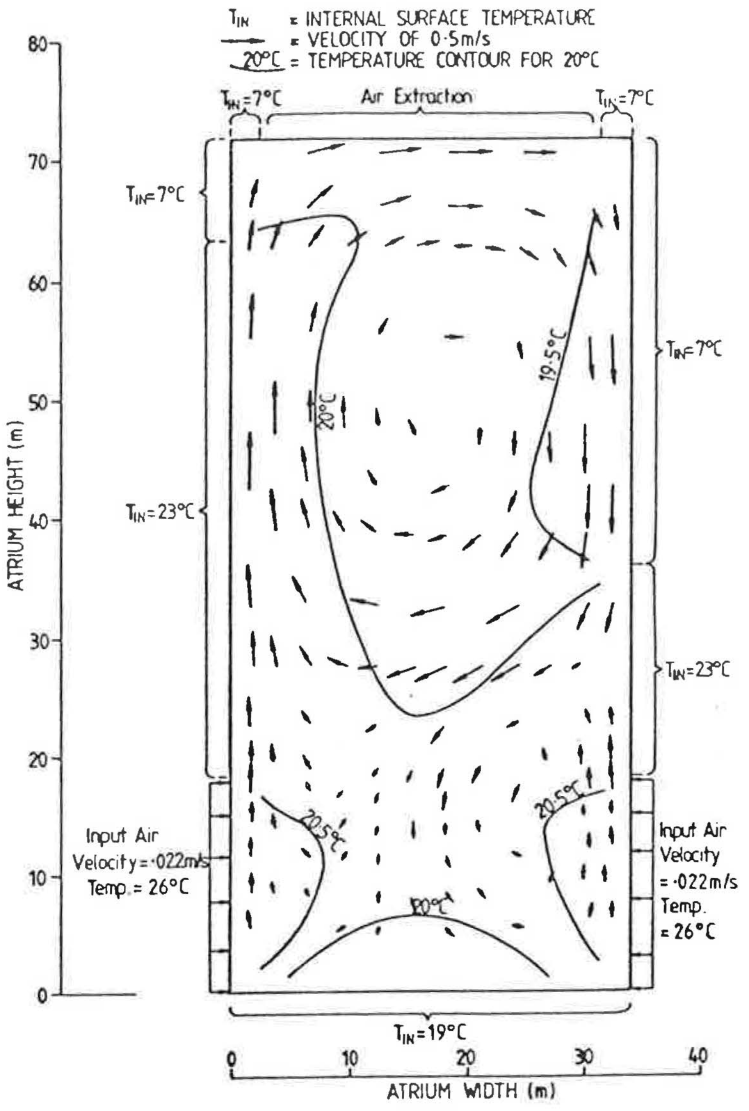


Figure 7.6 *Velocity and temperature fields in the longitudinal slice*

Conclusions

The conclusion of this study was that there was only a remote chance of cold downdraughts penetrating the occupied zone and creating uncomfortable conditions. To cover even this remote eventuality provision was made for the addition of deflector shields above the seventh gallery onto the atrium.

Nomenclature

Gr = Grashoff Number
m = Real Number
n = Real Number
p = Pressure
S = Source Term
V = Horizontal Velocity
W = Vertical Velocity
x = Distance
y = Vertical co-ordinate
z = Horizontal co-ordinate
ν = Downward Velocity
v = Kinematic Viscosity
P = Density
μ = Effective Turbulent Viscosity
ϕ = General Property
Γ_ϕ = Exchange coefficient for ϕ

Air conditioning using a floor plenum: *Alisdair McGregor*

Introduction

The rapid increase in the use of computer technology in the modern office has forced services engineers to reappraise air conditioning strategies for new office buildings. In the seventies computing hardware was usually located in special clean rooms which could be conditioned by a separate air conditioning system. This system could be designed to provide the correct temperature and humidity conditions for machine operation with occupant comfort criteria such as air velocities and minimum supply temperatures of secondary importance. The last five years has seen computer hardware move into the general office environment. A few years ago equipment gains of 10W/m^2 were considered adequate for most offices. Today 20W/m^2 is a common figure used for general offices and the dealing rooms currently appearing throughout the City are going above a 100W/m^2.

Reasons for choosing an underfloor supply

Early design solutions for Lloyd's included medium pressure, high velocity variable air volume, all air cooling systems serving both the core and overlapping into the perimeter areas. However, the following problems were encountered:

- The volume of plant at high level on the satellite towers.
- The size and quantity of distribution ductwork and its support system.
- The integration of air conditioning terminal equipment with the coffer and the facade.
- The projected energy consumption of the building, of the order of 1.0 GJ/m^2 which, even allowing for special Lloyd's factors of high population densities, in-house catering etc., was considered to be unacceptably high.
- High air velocities in the occupied region.

The volume of electrical and data trunking and the client's brief for flexibility of services had already demanded a raised access floor. Therefore an air conditioning system using the floor plenum was investigated. Previous work by H. Spoormaker (5,6) noted the following advantages of a floor supply/ceiling extract system.

- Elimination or reduction of ducts by the use of the floor plenum for air distribution.
- The use of heat exchange between the cool air in the plenum and the concrete structure to provide thermal storage in the structure and thus reduce peak cooling loads.
- Reduction or elimination of smoke and odour nuisance from other space occupiers through localised or workstation air supply.
- Wider effective individual temperature control range than a conventional ceiling distribution system.
- Simple system adaptation. Local high load areas can be catered for by plug in cooling units.
- If fan powered air terminals drawing air from the plenum are used then some cooling effect can be maintained if the chillers are off because of the thermal inertia of the floor slab.

By coupling the office space to the floor slab, the thermal environment of the office is very stable. This stability allows the design temperature of the occupied region of the offices to gradually increase during the day. At peak conditions the temperature floats from 19°C at 9 a.m. to 23°C at 5 p.m.

With a floor supply ceiling extract system a large proportion of the lighting convection gains do not enter the occupied region. Furthermore, the natural buoyancy of the air warmed by convective gains from people and machinery is encouraged to rise by the general upward movement of the room air. The floor to ceiling height at Lloyd's is 3m and this allows a pool of warm air to collect between 2m and 3m above floor level. The result of this is that only a proportion of the convective gains have to be cooled by the air conditioning system. Furthermore, the system becomes more stable as air can be supplied at constant temperature and differences in room heat load manifest themselves as a difference in exhaust air temperature.

Incorporation of system into Lloyd's '86 building

The principles of the underfloor system are shown in Figure 7.7. Conditioned air brought down the external ducts from the plant rooms on top of the satellite towers is pushed out into the floor plenum from header ducts. Small fan units within the plenum, known as fan air terminals (FATs), take approximately a half and half mix of primary air and recirculated room air and deliver the mixed air via flexible ducts and circular Krantz twist grilles to the room. Air is extracted at high level through the luminaires and taken along ductwork to the glazing where the warm air passes down the inner cavity of the triple glazing and is then collected in header ducts and taken back up the external ducts to the plantroom. At underwriting levels the additional volume of air required for the high occupancy density is allowed to escape into the central atrium.

The heat pumps shown at the base of the glazing are water/air reversible units. They are used to provide cooling in the perimeter zone to counteract solar gains and also morning warm up in winter. The heat pump water circuit is oversized so that additional underfloor heat pumps can be added to provide local cooling to high load zones. In underwriting levels a chilled water circuit is provided to cater for future increases in computing equipment on the floor as predicted by a report on the uptake of information technology by the insurance market.

The design gains for the underwriting levels are as follows:

- Lighting 20W/m^2
- Equipment 20W/m^2 + 30W/m^2 with chilled water circuit
- Residents 25W/m^2
- Visitors 38W/m^2.

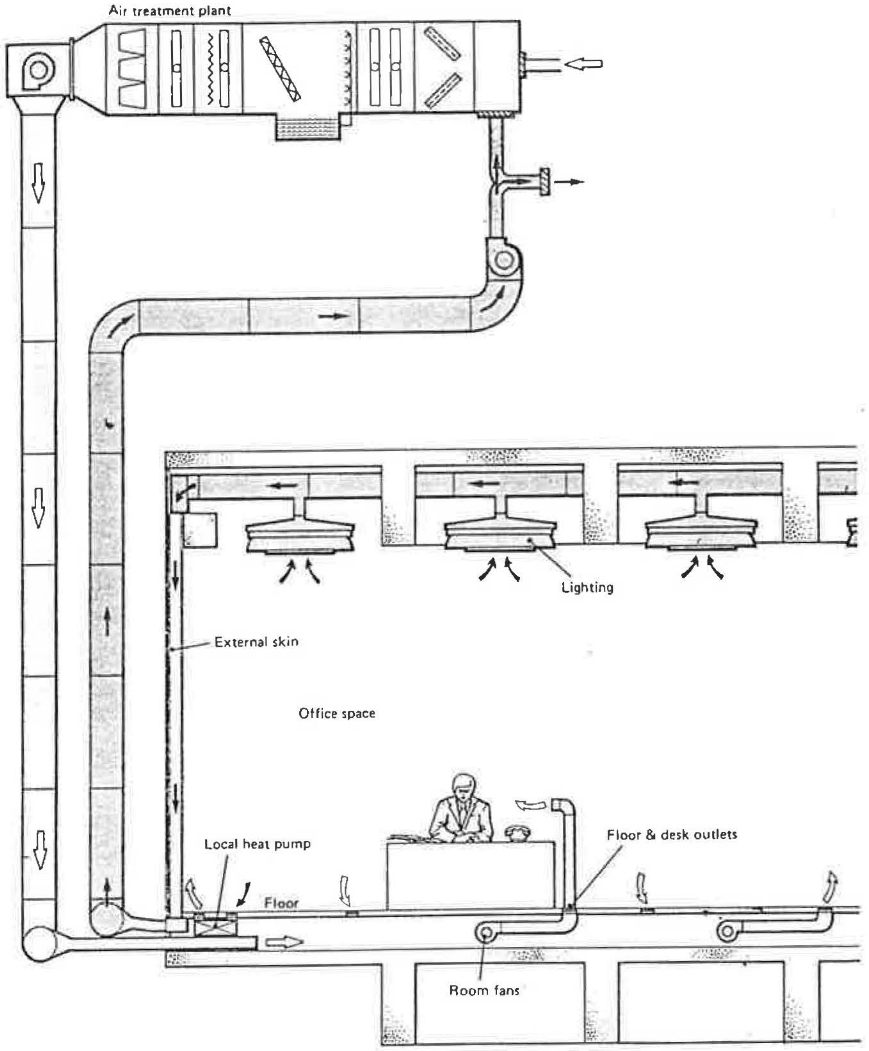


Figure 7.7 *Principles of underfloor supply to office areas*

The design gains for office areas are as follows:

- Lighting 20W/m^2
- Equipment: 25% of floor area at 60W/m^2
- Equipment: 55% of floor area at 10W/m^2
- Equipment: 20% of floor area at 0W/m^2
- People 8W/m^2

The final design of the luminaire has resulted in a lighting gain of 15W/m². The occupancy gains for underwriting appear high, however, a glance into the existing room shows how densely packed it can become. To cater for these gains a supply air temperature of 14°C is required to keep primary air volumes down. This is too cold to supply at floor level hence the requirement for fan air terminals to mix room air and primary air in the floor plenum and supply air off the grille at 18°C. Exhaust temperature can exceed 30°C under full load. High exhaust temperatures cannot be achieved with ceiling supply systems as the supply air mixes with the hot air at high level before entering the occupied region.

Slab performance

Computer simulations were carried out to establish whether the concrete floor slab could be used to store "coolth" overnight and thus reduce the load on the chiller plant during the day. A finite element program was developed to enable the thermal influence of the structural slab and raised floor on the room air temperature to be evaluated.

Computer simulations were carried out to see if running supply fans at night time in summer would reduce room temperature during the day. A series of 5 consecutive hot summer days was modelled. By running the main fans for substantial periods at night, the daytime off coil temperature could be increased to 15°C. Without nighttime fans the off coil temperature needs to be 13°C.

A comparison between systems was made based on worst case conditions with an external diurnal range 16–28°C, a main fan power efficiency of 80% and a central refrigeration plant COP of 3. The results show that from an energy conservation standpoint the Lloyd's slab is of marginal benefit in peak summer conditions but could be beneficial for substantial amounts of the year.

The system is designed with an off coil temperature of 13°C so that should off peak electricity charges make nightime fan operation uneconomic, comfort conditions can still be maintained. The building automation system enables the main fans to run at 12.00 p.m. when the highest floor slab temperature is at a higher temperature than the outside air by amount set on the BAS, typically 2/3°C. As soon as the slab has cooled to 15°C then the plant shuts down. If the outside air temperature drops below a minimum then the plant shall shut down.

Feedback from the BAS when the building is operational will provide data on the economics of nightime slab cooling.

Testing an office module at BSRIA

The Building Services Research and Information Association (BSRIA) were commissioned to carry out an experimental investigation to establish the air velocities and temperature gradients of two different systems; one employing Krantz floor grilles, the other conventional linear grilles.

The test room is shown in Figure 7.8. It consisted of a standard 2 × 2 coffer office (3.6 × 3.6m). Six tests were completed and the averages of the air velocities were less than 0.2m/s which are within CIBS recommended values.

As the room air temperature gradient was of primary interest in the investigation, the room was divided into different zones and the average air temperature was evaluated for each zone.

The following three zones were considered:

- A lower zone up to 1.5m height representing the occupied zone for a seated person.
- An upper zone between 1.5m and 2.9m.
- The ceiling-bay zone above a height of 2.9m.

The test results are only applicable to the particular circumstances of the test because there were heat flow paths in the test model that do not exist in the real building. The only satisfactory method of extrapolation from test model to real building was to construct a mathematical model. The model split the room into the three zones as above and considered all radiative and convection transfer between zones and surfaces. Table 7.1 shows the comparison of experimental and calculated results. The agreement in the case of the test using Krantz outlets is good.

Table 7.1 *Comparison of measured and predicted temperatures*

	Laboratory Temperature °C		Lower Zone Temperature °C		Extract Air Temperature °C	
	Test	Required*	Test	Predicted	Test	Predicted
E	26.5	27.5	22.0	21.8	27.7	27.7
F	27.0	26.5	22.3	22.3	27.3	27.4
G	23.8	22.5	22.2	21.5	27.2	27.4
H	23.9	24.5	22.5	22.2	27.1	26.6

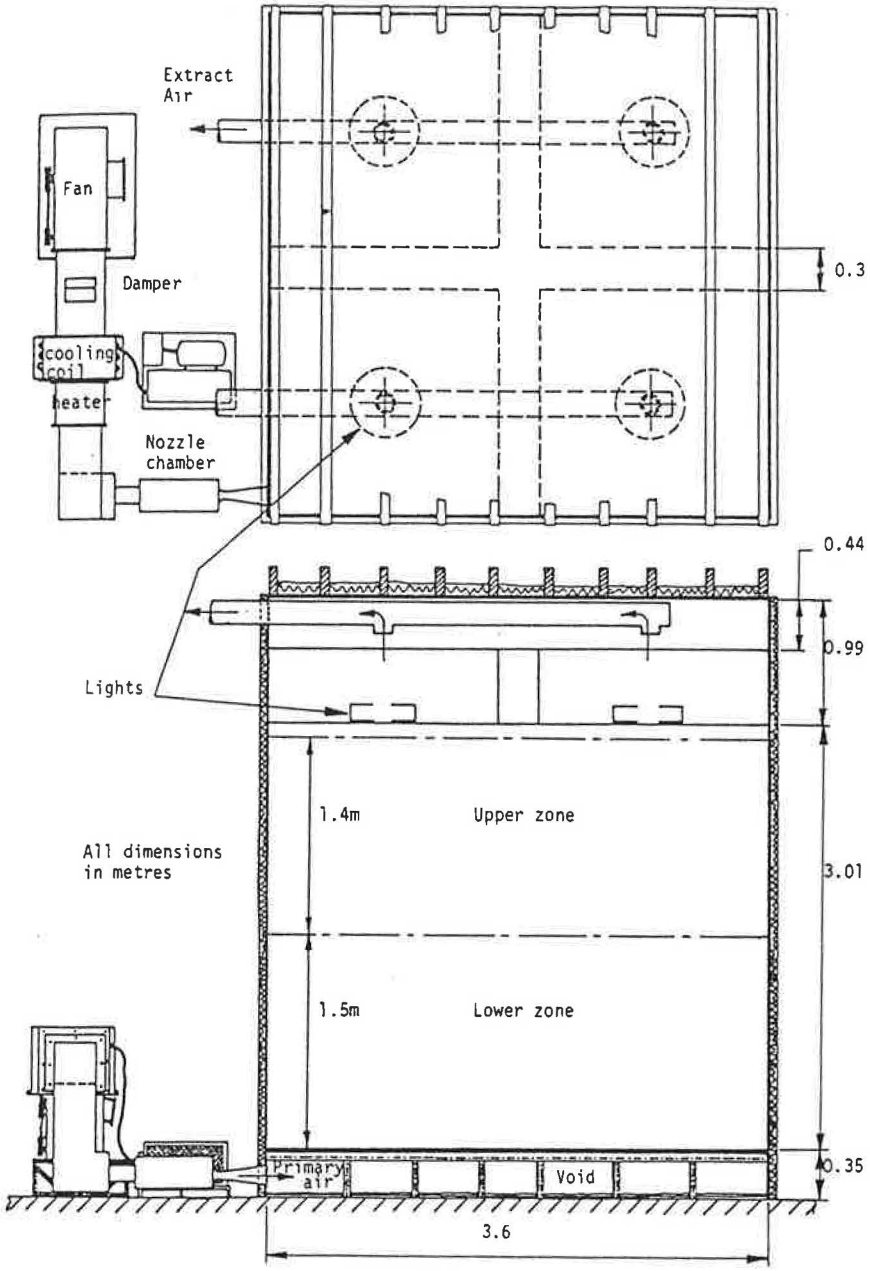


Figure 7.8 *Layout of test room at BSIRA*

The efficiency of extraction of convective heat is 60%, thus only 40% of the convective gain from the lights reaches the occupied area.

Table 7.2 presents the predicted temperature for:

Primary air	0.264m^3/s
Recirculation air	0.021m^3/s
Primary air temperature	14°C

Head loads:

Lighting level A	20W/m^2
Lighting level B	16W/m^2
Occupants and equipment	12.6W/m^2
Recirculation fan	2.5W/m^2

In order to obtain the correct trend of results, it was necessary to adjust the temperature required in the laboratory. This is to be expected, as a single measurement of laboratory temperature cannot be taken as representative of all conditions surrounding the test model.

Table 7.2 *Predicted space temperatures*

	Space temperatures °C			
Lighting Level	Supply Diffuser	Lower Zone	Upper Zone	Extract Air
A	20.9	23.0	23.8	29.6
B	20.2	22.0	22.7	27.9

The temperatures above relate to steady state conditions within the space. Thermal storage of the structure will reduce these values.

The results from BSRIA showed the floor supply system provided temperatures around 22–23°C in the occupied zone without draughts except directly above the floor grille. Smoke tests showed that good mixing took place with both Krantz and linear grilles. Temperature gradients from the test are shown in Figure 7.9.

Servicing the underwriter's box

In underwriting areas a large area of the floor is taken up by the under-

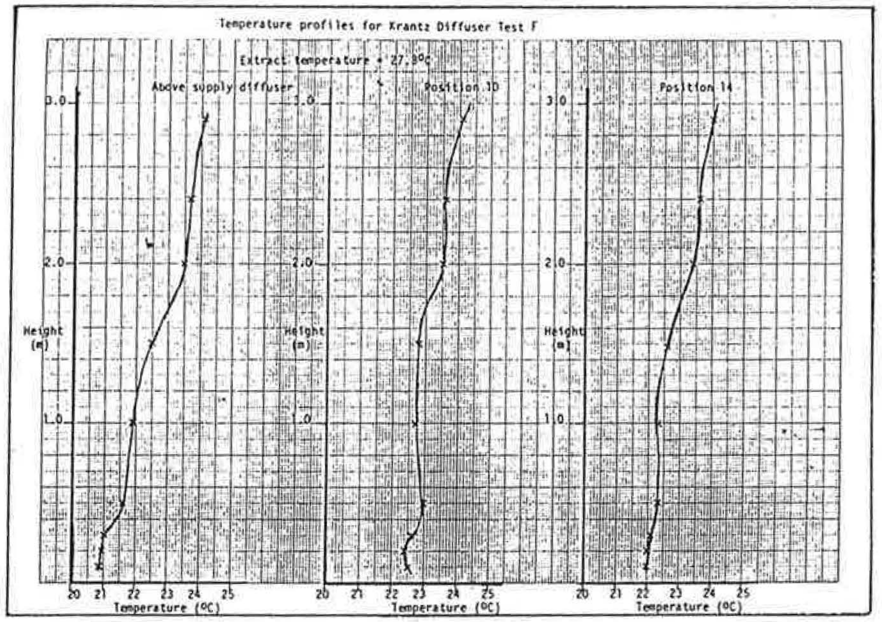


Figure 7.9 *Vertical temperature profiles*

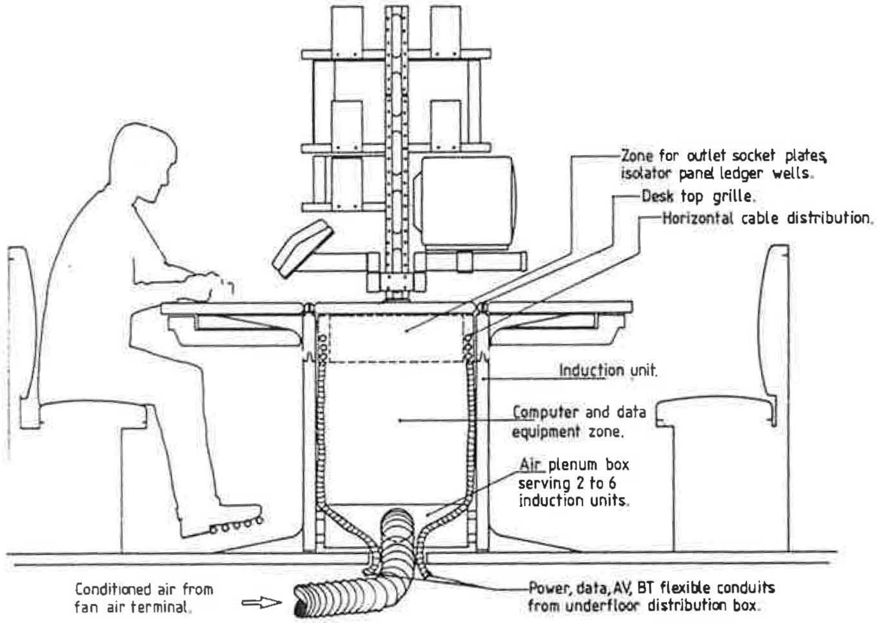


Figure 7.10 *Underwriters box principles of services*

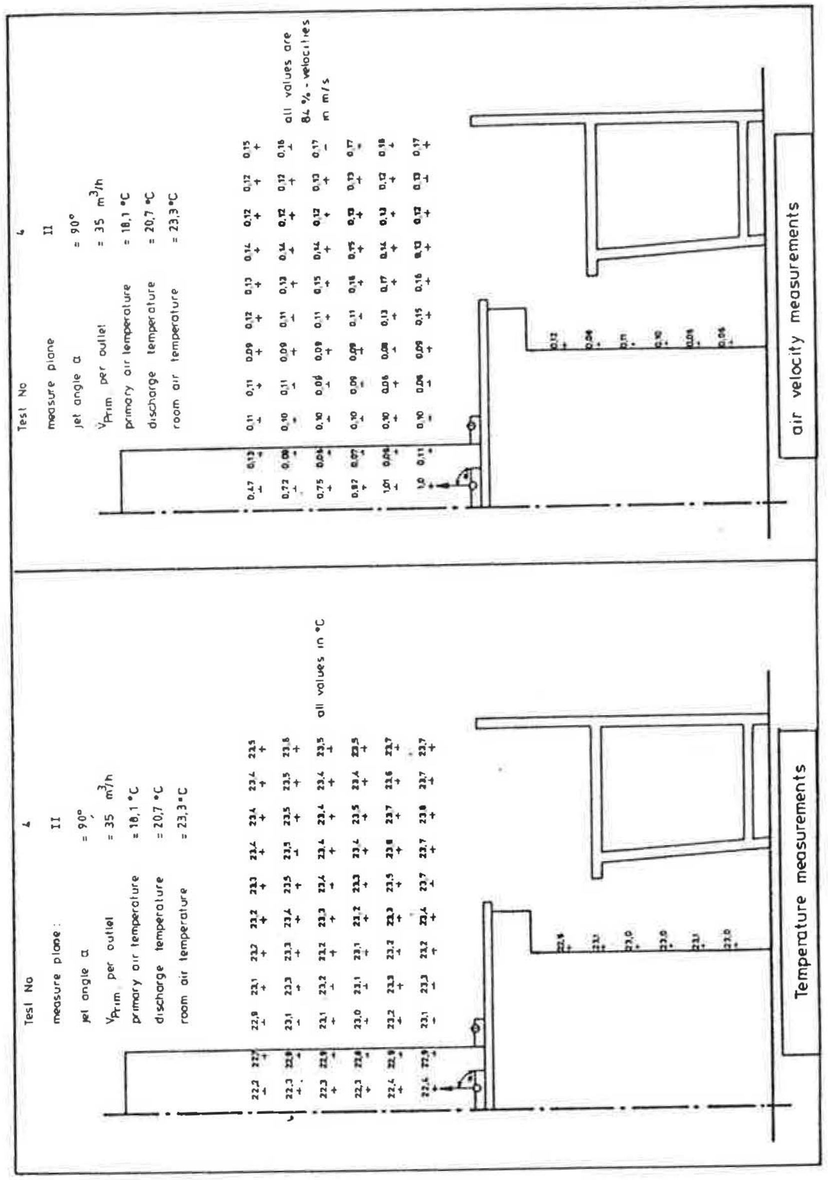


Figure 7.11 *Test results of prototype*

writer's desks or "boxes" as they are known and their seats and cupboards, leaving less floor space available for floor grilles. As most of the business takes place at the boxes, the new boxes have been designed to incorporate air conditioning, computing equipment, data, telephone, audiovisual, and power cabling. The principles of the box design plugged-in to the floor is shown in Figure 7.10.

Work by Dr Franc Sodec of Krantz has shown that if supplying air at desk level a primary air volume of $35m^3/hr$ at 18°C minimum per person will provide comfort conditions. 18°C is too cold to supply at desk top level so an induction unit is provided resulting in an off grille temperature of 20°C + 0.5°C with a mean room temperature of 23°C. A prototype was tested and temperature and velocity profiles are shown in Figure 7.11.

Application of a direct digital control (DDC) system to a complex building: *Martyn Harrold*

Direct digital control is the use of software based algorithms, to achieve on/off, proportional, proportional plus integral and proportional plus integral plus derivative action control loops. Often, as in the case of the system employed on this project, the software includes all control strategies with the exception of the safety interlocks.

The Lloyds 1986 Building, due to its size, geography, complexity and the Client Brief requires a Building Management System to enable the engineer to maintain and operate the system as the designers intended.

The system is required to control:

- 45 air handling systems
- 900 perimeter heat pumps
- 1600 Fan Air Terminals
- 10,000 lighting fittings
- 7MW of heating
- 4.2MW of cooling
- 6MW of electrical input
- 3MW of standby generation

When considering the type of control system to apply to the building the options of pneumatic, electronic or DDC were considered.

The absence of terminal units from the air conditioning design eliminated any cost advantage that a pneumatic control system might have offered leaving just the fail safe very powerful actuators as an advantage over electronic/DDC control systems.

Electronic control systems are more accurate than pneumatically operated ones but neither interface neatly with a Building Management System.

Direct digital controls are more accurate than any other, they are also more flexible and far more able to cope with complex operating regimes.

Many of the problems associated with installing and commissioning a BMS/DDC system in a large complex building were expected and provision made in the contract. However some unexpected problems arose and others which were expected and for which no provision could be made in the Contract.

The first problem encountered was that of jargon and the definition and even interpretation of that definition. It is imperative that the Specification defines technical words and that this definition is the only one to be used in the Contract.

The next problem was the *what happens if* syndrome. With a conventional control system, either pneumatic or electronic the logic is defined in hardware and the sequence of action in the event of failure is very limited. Once this interlocking and control is achieved through software there are many more options available and what happens going up need not necessarily happen in reverse going down and conscious decisions have to be taken for each and every step of the logic process.

With a pneumatic or an electronic control scheme drawings are submitted for approval which show the interlocking between frost thermostats, timeswitches, fans, smoke detectors, pressure switches, firemans control switches and which show the way the controls move in the event of plant shutdown or failure. Approval of software is a major problem. The software listing for the DDC loops excluding the Building Management System functions exceed 15,000 lines of code written in a high level language unique to the supplier. Even after a two week full time training course at the manufacturer it would not be possible to approve the software and yet some checking is imperative. The only acceptable solution to this problem is to check but not approve the software listing and then at the end of the project witness each and every point being demonstrated by the contractor. To illustrate the commitment which must be made it has been estimated that this will take 250 days for two men from the Engineer/Client plus the same again for the Contractor. This has raised serious contractual problems relating to practical completion and handover. It is important to stress that all points must be checked because experience to date on other projects shows that when a contractor offers a completed BMS for acceptance normally only 50–80% of the points are correct.

One further difficulty on the subject of acceptance testing software based systems occurs when a fault is discovered in the software. A copy of the software must be downloaded from the system onto disk or tape because instances have occurred whereby previously checked and accepted parts of the system have been corrupted by the software patch. There is no way out of this dilemma as it is clearly impossible on a large system to recheck all previously checked work.

Normally on a contract with a BMS it is not essential that the BMS is up and running before the air conditioning systems and other services are commissioned.

However when the control system is combined with a BMS installation it is vital that the system is operational six months prior to practical completion to allow control valves and dampers to be moved for flushing draining and balancing. To achieve this it is necessary for the Main or Management Contractor to get the BMS control room complete, clean and secure together with its associated ventilation system completed 6–9 months prior to practical completion.

A control engineer is required to have a good understanding of air conditioning systems and plant from an electrical as well as a mechanical point of view but to date it has not been necessary to have the ability to program. DDC Systems above all else require this ability and the industry is meeting this problem by employing programmers and unfortunately programmers do not yet have the necessary feel for Buildings and their services and it will be two or three years before this problem begins to recede.

The whole process of specifying-approval-testing and commissioning needs to be looked at carefully. The best approach is to use flow diagrams.

It needs to be said that the above description has been significantly simplified in order to highlight the salient points and avoid being bogged down in the many technical problems, conflicts and details and their solutions in the Lloyds 1986 Building.

References

1 D.J. Tritton, *Physical Fluid Dynamics*, Van Nostrand Reinhold, 1980.
2 D.B.S. Spalding, *Phoenics Manual*, Cham Limited, Bakery House, Wimbledon, London.

3 N.C. Markatos & C. Pericleous, *Laminar & Turbulent Natural Covection in an Enclosed Cavity*, Int. Jnl. Heat & Mass Transfer, Vol. 27, No. 5, p. 755–762.
4 W. Rodi, *Turbulent Buoyant Jets & Plummes*, Pergamon Press, 1982, Page 147.
5 Herman, A.F.E. & Spoormaker, H.J. – *Plenum Air Conditioning Systems*, Ove Arup & Partners, South Africa 1981.
6 Spoormaker, H.J. & McMillan, C.M. – An energy efficient flexible system for HVAC and electrical services – *Heating, Air Conditioning & Refrigeration* – March 1985.