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AIR CONDITIONING AND THE EVOLUTION OF MODERN OFFICE BUILDING DESIGN

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Air conditioning, as we know it, providing thermal comfort by mechanical means, first appeared in buildings about one hundred years ago. During that time it has had major influence on the evolution of the design buildings. This paper reviews the development of providing cool comfort in office buildings from the pre-active era of the middle of the 19th century through the rise of air conditioning in the mid 20th century to the current state of the art. The development has been sporadic punctuated by technological innovation, responses to energy and environmental issues and, changes in architectural fashion. The paper concentrates on the essential interdependence of the design solution between the building and the air conditioning system and what we can learn from both success and failure.

INTRODUCTION

The description "fully air conditioned" is almost synonymous with large prestigious buildings, offices in particular. However, with very few exceptions, such large buildings did not exist before the middle of the 19th century. Until that time offices were most often a few rooms in a converted dwelling house. The exceptions being large public buildings for government administration in London and other major cities(1). During the second half of the century the growth of commerce in general, and insurance companies in particular, meant that large buildings were needed to house the rapidly increasing numbers of clerical and administration workers(2). By the end of the 19th century offices had evolved as a distinct category of building purpose designed to house clerical and administrative activities.

The internal environment enjoyed or endured by these early office workers was determined, to a large extent, by intrinsic features of the buildings such as fenestration, plan form, storey height. Protection from the extremes of the climate was restricted to passive measures such as opening windows and lowering shades when it was hot and open coal fires or stoves, and eventually radiators, when it was cold. The intrinsic features were, in turn, determined by a number of other factors which included finance, function, location, current technology and architectural fashion.

Although external sun shades were common on buildings in Europe and North America in the 19th century, keeping cool did not seem to be a major concern. The priorities were adequate ventilation for sanitary purposes(3) and eliminating excessive humidity(4). The latter applied particularly in the USA in cities with warm humid climates.

Even though electricity was common by the 1890s office work was still largely carried out by daylight. The ability to illuminate the full depth of the offices was, therefore, one of the most important provisions. Although it limited the maximum width of office between the outside wall and the internal corridor, it meant that natural ventilation was available by way of the opening windows. The need to provide daylighting was also a major constraint for architects and property investors attempting to obtain the maximum office floor area from building plots.

In retrospect, the chance to use air conditioning, in conjunction with artificial lighting, must have offered great opportunities to transform buildings: to design buildings without the constraints of passive measures, to provide comfortable internal environments irrespective of the type and size of enclosure and, to create offices of infinite depth without regard for fenestration. On the other hand air conditioning means: ducts, plant and equipment that occupy valuable space, it increases the initial and running costs, uses more energy, does not always work and has to be controlled and maintained.

How did architects and designers respond to these opportunities? What were the effects on the buildings? And, were the occupants any more comfortable?

PRE-ACTIVE OFFICE BUILDINGS AND COOL COMFORT

Most large public, and many commercial offices, built up to about the end of the last century reflect the facades, proportions and plans of classical architecture. Many were based on designs that can be traced back 2,000 years or more and sharing, for example, characteristics with the houses described in Vitruvius's books of architecture(5). One example is the Foreign Office, built in London in 1867. It is a large building (see the floor plan in figure 1.), of about 60,000 m^2 floor area, in the Italianate style, to the design of the architect George Gilbert Scott.

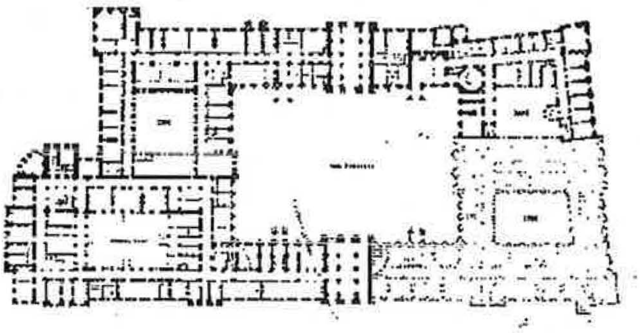

Figure 1. Plan of Foreign Office, c1867

It comprises a series smaller buildings, each with the plan form reminiscent of an Italian villa, each with a courtyard, around a large quadrangle. Each office has natural light and ventilation from the window and the rooms are limited in depth from the outside wall to the corridor to around 4m. The storey heights are quite magnificent with the piano nobile at almost 7m and even the lowest, on the third and fourth floors are around 3.5m. Fireplaces are arranged back to back to heat every office and the dividing walls are constructed from 9" brick to conceal the chimney flues. These features including the high ceilings and thermal mass of the building inevitably meant that the offices would be reasonably cool even during the height of an English summer. Large windows may have introduced some unwanted heat from the sun on the south face, however, contemporary photographs show them shaded, on the outside, with white linen blinds.

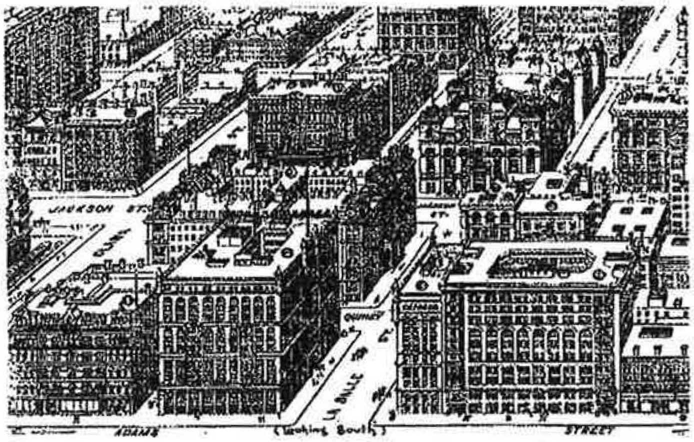

Figure 2. Chicago from Rand McNally Map 1898 (from ref.6)

This combination of classically proportioned facades and courtyards or light-wells was not peculiar to Europe. Most American architects of this era studied in Europe and adopted classical styles and proportions for their buildings. The use of light wells was quite prevalent, at the time, as it allowed property investors to obtain the best ratio of lucrative office floor area to plot size. They were particularly common in Chicago where height restrictions had been imposed to limit high vacancy rates, following an office building boom caused by the great fire of 1871. The Rand McNally map, in figure 2., shows some of these buildings in a section of the business district in 1898. The concept of maximising the window-lit offices was carried through to other styles of building that were evolving in other US cities. For example, at this time in New York putative skyscrapers were reaching heights of nearly 400 feet but the shape and size of the floor plan was still constrained by the need to provide adequate daylight for clerical work.

MECHANICAL VENTILATION

Ventilation and the need for adequate supplies of fresh air were a pre-occupation of heating and ventilating engineers in the 1890s(3) and, as a result, mechanical ventilation had been introduced into many of the new larger buildings.

At a meeting of the fledgling American Society of Heating and Ventilating Engineers(ASHVE) in 1899, the author of a paper entitled "Some Points Regarding the Ventilation and Heating of Tall Buildings" (7) commented that he had visited many offices in the most recent buildings and "when entered from the outside air they appeared to possess at least some of the qualities of menageries...." He was referring to the smell and thought that it was a sure sign that ventilation was needed. In the context of the paper he meant mechanical ventilation. He also described the types of mechanical ventilation systems in use in tall buildings in the USA at that mentioned the problems of accommodating ducts. Some systems relied solely on exhaust ducts and extract fans with natural inlets, others had blast(supply) fans with natural exhaust and one novel plant he cited, in a building in Buffalo, used the ventilation plant to entirely heat and ventilate the building i.e. without using radiators. He suggested, with foresight, that an ideal solution for such systems would be to have "double-ducts" one hot and one cold.

The leading exponent of the design of mechanical systems in the US at the turn of the century, and responsible for the "all-air" ventilation system at Buffalo, was Alfred R. Wolff. He was designed about 100 systems between 1889 and his death in 1909(8). It is interesting to note that these tall buildings were not mechanically ventilated throughout. For example, the 21 storey American Surety Building in New York, completed in 1896, had a mechanical warm air supply and extract ventilation system providing four fresh air changes per hour but, it only served the lower seven floors. The rationale was that lower floors suffered from the noise and smells of the street and the occupants could not open windows for relief. The practice continued into the early air conditioned skyscrapers of the late 1920s and 1930s.

It is also interesting that the problem of office overheating was not mentioned in the paper, nor raised in the discussion. Particularly as a comprehensive paper on, "the cooling of closed rooms"(4), had been presented at a meeting of ASHVE the previous year and a few mechanical cooling installations had already been completed(8).

THE LARKIN ADMINISTRATION BUILDING

The first office building that broke the mould was the Larkin Administration Building designed by Frank Lloyd Wright and completed 1906. The brief from the client(9) required a sealed building with mechanical ventilation, there was no mention of cooling, but Wright's specification for the building included a refrigeration plant that distributed cooling water at 10°C to air cooling coils in the air handling plants(9).

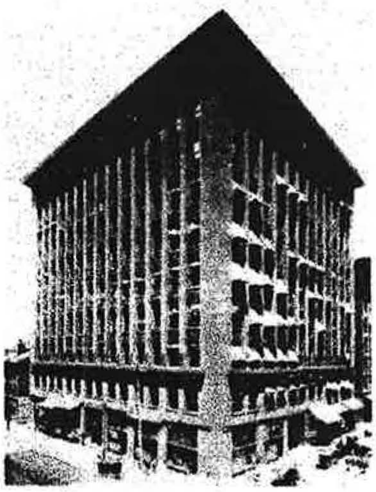

fig.3. Wainwright Bldg.(1891)

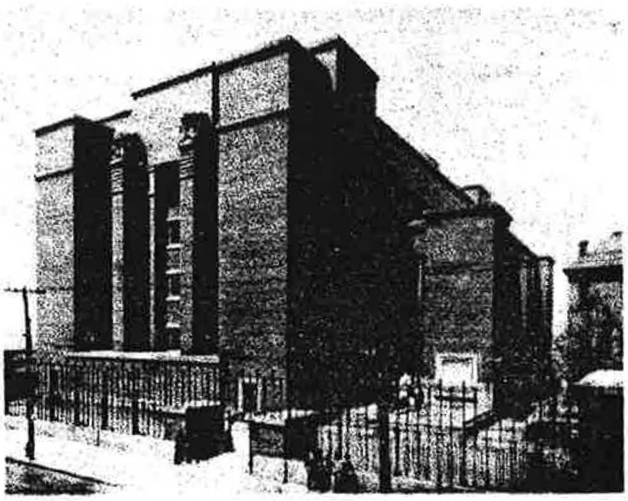

fig.4. Larkin Administration Building

The appearance of the building was dramatically different from architectural fashion at the time. Most architects, in the USA, were still designing offices in the "Beaux Arts" style with heavily ornamented facades. This was a large squat building that Wright described, in his 1943 biography(10), as a "simple cliff of brick hermetically sealed (one of the first 'air conditioned' buildings in the country)."The term "air conditioning" was practically unknown in 1906 and did not come into common use in the late 1920s, at the earliest.

In terms of the "massing" of the building, it resembled the "Chicago Quarter Blocks" that Wright was involved with when he worked in Louis Sullivan's architectural offices in the 1890s. These buildings were so called because they just filled the width of the blocks between streets. The style was exported to many other cities in the USA. Louis Sullivan's Wainwright Building in St. Louis is a well known example reputed to be a model office building of its time(11). It is shown in an early photograph, in figure 3., with sun shades extended.

The Larkin building had a basement and five floors above ground and, as was common with the Chicago Quarter Blocks, a large internal light well, or light court as they were called, provided daylight to inner spaces on the floors above ground, even though this was one of the earliest buildings to have general, artificial lighting. The large windows had an unusually high sill, 1.5m above the floor level, and no solar shading, in contrast to most buildings of the period. The mechanical ventilation system provided heating and cooling by 4 to 5 changes of full fresh air per hour treated in basement air handling plant. Air was exhausted the air from the offices at floor line in winter and from the ceiling in summer, presumably to maximise the respective heating and cooling effect. Although the cooling power was not great, by comparison with some more recent systems, one can speculate that intrinsic features of the building would have meant that it was a cool and comfortable even in the heat of summer. These features include: the generous floor to ceiling height of 4m, the "thermal" mass of the walls and ceilings and the recessed windows which all contribute to cool comfort. The only area where there was likely to be a lack of comfort was on the west side where clerks would have been in direct sunshine on summer afternoons.

The Larkin building was probably the first, specifically designed, to accommodate all the paraphernalia associated with modern air conditioning. Services ducts, running from basement to roof, were sited adjacent staircases and expressed on the outside of the building. The ducts handled air drawn in and exhausted at roof level. Columns were extended with false sections to house steel supply ducts. Large areas of the basement were allocated to water storage and to air handling plants.drawing air from the top of the building. Interestingly however, although Wright specified a refrigeration machine space was not allocated on the basement plan. This begs the question, was he the first architect to under-provide space for air conditioning plant?

From the perspective of the history of air conditioning this building is unique. Wright's design, which included working drawings of the ducting and plant, resolved many of the major issues decades ahead of other architects even considering them.

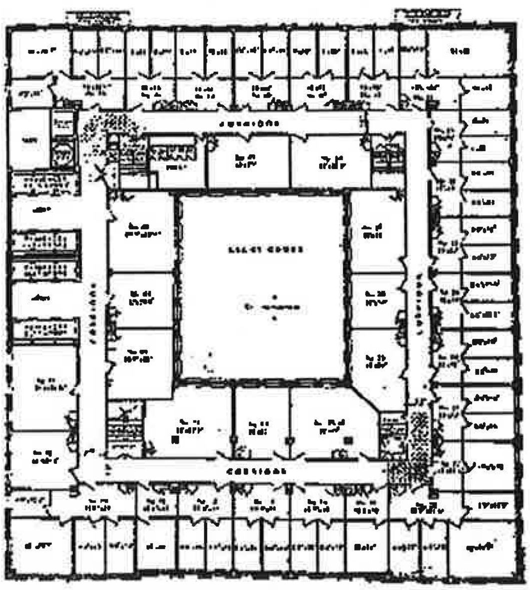

fig.5. Straus Building (1924)

NATURALLY VENTILATED SKY SCRAPERS

Although the Larkin Building was reported widely and well received critically the development of air conditioning in offices languished for the next twenty years. However, by the mid-1920s, air conditioning, even though it was still not known as such, was being used regularly in theatres, hotels and department stores, but not in new offices. This despite building boom periods in the US before World War 1 and the late 1920s. In effect, the skyscraper "as we know it," evolved without the benefit of air conditioning. Classic buildings such as the Woolworth and Chrysler reached unprecedented heights relying on passive techniques to provide lighting and ventilation. The need to provide natural daylight to offices was still paramount.

As a prelude to the construction of a new headquarters and investment property for a banking and investment company in Chicago in the mid 1920s, an extensive study was carried out to attempt to obtain the most efficient office building, i.e. to achieve the greatest office area for a given cube of building(6). The constraints were the plot size and the local building height limitations. The result was a 21 storey building with a large light court surmounted by a nine storey tower. The square block plan with a light-court proved to be more efficient in space terms than the other plan forms such as "E","H" and "U" in use at the time.

The effective depth of rentable office was increased by siting ante rooms between the window lit office and the corridor. This was common practice in the USA, probably as a consequence of filling the large floor plan area generated from the street planning grid. A typical arrangement allowed two windowed offices and a "reception" area in a regular "T" shape. The reception space was used for secretaries and these "second-class" workers had to rely on borrowed light and ventilation from the outer office. The final building is shown in plan in figure 5. on the previous page. It was called "The Straus Building" and was advertised as "Chicago's Finest Office Building" at the time. It is surprising that air conditioning was not included as only two years later what was claimed to be the world's first fully air conditioned office building was completed in San Antonio.

THE FULLY AIR CONDITIONED OFFICE BUILDING

A new magazine was launched in 1929 called "Heating Piping and Air Conditioning"(HPAC). The title and the relative position of the words "air conditioning" is probably a sign that the term was coming into common use. The lead article in the July issue(12) proclaimed the Milam Building as the "first in the country to be completely equipped for air conditioning to provide year-'round comfort" what we would now describe as fully air conditioned. It was certainly air conditioned but all the main features of the building, form, fenestration, floor plans etc. belong to the pre air conditioning era.

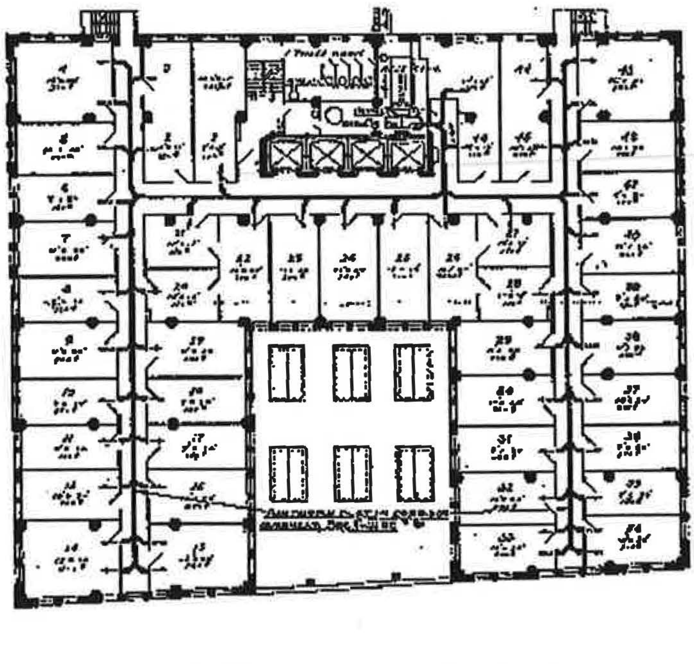

figure 6. Milam Building (1929) Typical floor plan showing ducts.

There is some difficulty in applying all of the text of this particular article to the building in question as the author appears to mix his own views and philosophy for air conditioning with information on the actual building and its air conditioning system. However, it is interesting to note that he advocates the use of (external) blinds in an air conditioned building. Although none are shown in contemporary photographs he was decades ahead of his time with his advice.

The air conditioning system had several interesting features. Condenser cooling water was provided from the adjacent river, a chilled water storage system was charged overnight and chilled sprays were used to cool and dehumidify the air. In addition, occupants of the offices could choose to either open the window or the air conditioning register or both. Perhaps a very early form of "mixed mode." The system was also used to heat the building by warm air.

A plan of the duct distribution is in shown figure (6). Ducts were housed in a false ceiling, which formed a bulkhead, lower than the main office ceiling. Air was supplied to the offices from side-wall outlets at high level returned to the fan room via transfer grilles and along corridors. The amount of fresh air make-up could be adjusted by hand. The refrigeration unit had a cooling capacity of 300 TonR and, when related to the area of 20,000m^2 it seems quite small. The maximum rate of cooling would have been about 54w/m^2 and, taking into account the outdoor design condition of 36°C db and 23°C wb., the design of the ductwork and the poor air distribution it is unlikely that the occupants of the offices in the south west corner enjoyed the benefits of a fully air conditioned environment. Perhaps the ability to open windows was a significant factor.

AIR CONDITIONING AND THE INTERNATIONAL STYLE

Although the office workers in the Milam Building might not have received the full benefits of air conditioning they were considerably better off than the "poor souls" in the Salvation Army Hostel being designed by Le Corbusier and Jeanneret at bout the same time. Le Corbusier had been collaborating with a friend, Gustave Lyon who was developing air conditioning in Europe, independent of the "experiments" in the USA(13). Lyon had successfully completed the air conditioning for a 3000 seat auditorium with his system which he called *l'air ponctuel* and loosely translates as "regulated air." Le Corbusier had, he claims, invented a technique for cancelling the cooling effects of the large glazed surfaces characteristic of the new architecture, subsequently called the "International Style." Le Corbusier's idea was to circulate air at a constant temperature of 18°C between the panes of double glazed windows. He called it *le mur neutralisant* (neutralising wall) and coupled it with Lyon's regulated air for a design for the Centrosoyus Palace in Moscow. The combination was called "conditioned air" which Lyon thought was "an idea of genius." The Russians obviously did not agree as they ignored the proposal and simply placed radiators behind the large opening windows.

The opportunity to use the concept came with the commission for the *Cite de Refuge*, a Salvation Army shelter in a sinister quarter of Paris. Le Corbusier had conceived the idea to hermetically seal the south face of the building, from floor to ceiling and wall to wall with a thousand square metres of glass. His view was that the glass could be hermetically sealed as "warm and cleaned air circulated abundantly inside.." He was giving these poor souls "the free and ineffable joy of full light and the sun."

The building was eventually opened late and over budget on 7 December 1933, in one of the coldest periods in memory. The temperature inside was perfect, unfortunately the same could not be said during summer. Although the designers had intended providing their version of air conditioning the budget did not run to providing the cooling plant and the neutralising wall seems to have been omitted(14). Sealed windows did not comply with the regulations and ultimately, much to Le Corbusier's displeasure the windows were changed to opening. It appears that this experience changed Le Corbusier's ideas about glazing, his subsequent buildings featured shading which was eventually fitted to the hostel and he is attributed with inventing the *brise-soleil*.

THE PSFS BUILDING

The 32 storey PSFS Building in Philadelphia, completed in 1932, broke new ground in its architectural style and the concept of air conditioning. The appearance of the building was, at the time, considered modern and distinctly different from any other in the USA. The design reflected the "International Style"(15) with such features as: an absence of external ornamentation, cubic shapes and, relatively large area of metal framed, ribbon windows. Although the PSFS building shared these characteristics with Le Corbusier's Salvation Army Hostel and buildings by other leading architects of the time such as Gropius and Loos, it, unlike their buildings, was fully air conditioned.

Contemporary articles throw little light on why this building was air conditioned when other major buildings of the period were not. For example, in New York, the Empire State Building had only been completed a year earlier and the RCA Building, the centrepiece of the Rockefeller Center, had only just started construction, neither of which were air conditioned. The difference was most likely that the PSFS was purpose built for a prosperous savings fund society but the others were being built for investment. It was a period of severe recession in the US and property developers had still not identified any financial gain from installing air conditioning.

fig 7. PSFS Building (1932)

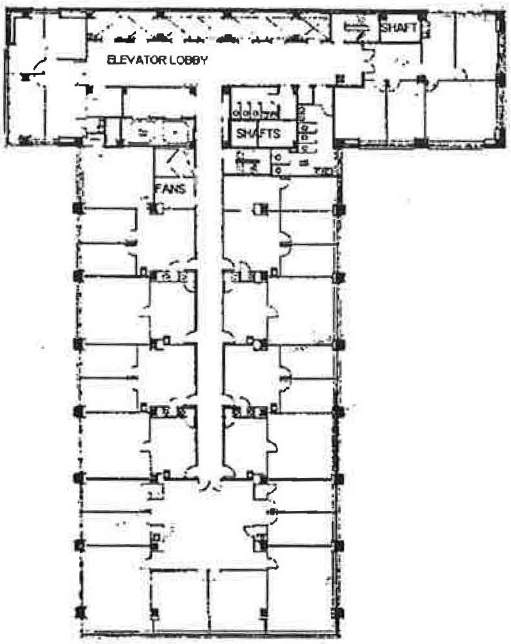

fig 8. Typical Upper Floor Plan

The design of the engineering systems at the PSFS Building included several innovations that pioneered the approach to servicing tall buildings. One of the most significant was the introduction of an intermediate level mechanical plant room floor at the 21st floor, in addition to the plant at roof level and in the basement. The concept reduced the space required for the vertical ducts by up and down from the roof, basement and intermediate plant floor. This division of the air supply plant dramatically reduced the floor space for vertical ducts.

Fresh, and possibly recirculated, air was supplied to floor fan rooms at each level. Each fan room had two fans, one to serve each of the east and west sides of the building. The fresh air was mixed with air drawn back through the corridors and recirculated to the offices. The intermediate plant room at the 21st floor also housed water tanks and reduced maximum pressure on the distribution pipes at lower floor levels. These techniques have been employed extensively in tall buildings ever since. Another feature was to provide thermostatically controlled heating beneath the window of each office instead of attempting to use the air conditioning system as a warm air heating system. This would have allowed the building to be pre-heated without running the air handling plants and provide an extra measure of local control and energy economy rarely seen before this time.

One can speculate whether the architects, Howe and Lescaze, demanded air conditioning to counteract the heat gain from the relatively large windows even though venetian blinds were an integral element of the design concept. This would make the PSFS building the earliest where air conditioning was installed to allow greater architectural freedom. However what is certain is that they used a novel architectural technique to conceal some of the air conditioning paraphernalia. The large "PSFS" sign on the top of the building, lit by red neon at night, is a Philadelphia landmark. And, as part of the original concept, it was used as a ruse to conceal cooling towers. Notwithstanding this, and with the possible exception of Lloyd Wright's Larkin Building, air conditioning achieved little impact on the appearance of buildings up to mid 'thirties.

GENESIS OF TERMINAL UNIT SYSTEMS

Even though siting mechanical plant at intermediate floors reduced the size of vertical ducts, the amount of floor space remained a major drawback, particularly in tall buildings. Willis Carrier recognised the problem in the 1920s and decided that high velocity air was the answer(16). He did not pursue it at the time but did develop a range of room terminal units intended to reduce the total volume of air circulated around buildings. They were housed in cabinets beneath windows and induced room air over a secondary heating coil. See figure 9.

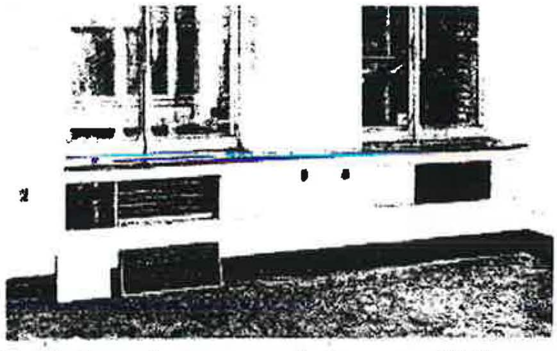

Fig. 9. Carrier's prototype induction unit of 1932

The supply air was cooled to a greater degree than would have been practical with air fed directly to the space and consequently reduced the "primary-air" flow rate. This reduced volume of primary air was ejected through nozzles which induced a secondary flow of air from the room over a heater coil that mixed with the primary and raised the outlet temperature to the space. This concept pioneered the decentralised terminal unit method of air conditioning still common today. In 1937 Carrier had the idea to connect these units to high velocity ducts to further reduce the size of main ducts and increase the induction of secondary air. He carried out a trial in one of the company's factories in 1937. Tests showed that the rectangular ducts leaked and they were changed to circular to improve the seal. Patents were applied for and the first installations were completed in 1940, only months before the USA entered the War and new building construction virtually ceased.

AIR CONDITIONING AND CURTAIN WALLING

The first building that integrated the design concept of large areas of glazing in a curtain wall and deliberately compensated for the additional heat gain by air conditioning was the Equitable Building in Portland, Oregon(17). It was completed in 1948 to the design of the local architect Pietro Belluschi. He intended keeping the windows free of blinds and used sea green glass with only 40% visible light transmittance to reduce the glare and heat gain to acceptable levels. The air conditioning system was one of the first to use reverse cycle heat pumps connected to wells to provide both heating and cooling.

The United Nations Buildings in New York was one of the first major building to be constructed after the War. A multi-national advisory committee was established for the design of the building, no doubt due to the bureaucratic nature of the organisation. It was called the Design Board and composed of a number of leading architects including Le Corbusier who allegedly claimed credit for the design concept. The Director of Planning and lead architect was Wallace K. Harrison who had experience of designing tall buildings from working on the Rockefeller Center development in New York. He was involved in a number of conflicts with Le Corbusier throughout the design, one of which was protection of the offices in the Secretariat Building from excessive solar heat gain. The Design Board were of the view that to maximise sun and natural daylight, overall glazing, i.e. a curtain wall, was the best solution. The Equitable Building was the only example of a continuous glazed curtain wall in the country and they were concerned about glare and heat gain. They considered four different glazing options in conjunction with internal venetian blinds. These included single and double glazing with and without tinted class. Le Corbusier was of the opinion that the tower building should protected from the sun by brise - soleil and faced in stone(18), perhaps as a consequence of his experience of experimenting with fully glazed facades on the Salvation Army Hostel in Paris. Brise-soleil were eliminated on the basis of the complications of snow collecting on them in winter.

To select the best of the glazing options Harrison turned the problem over to the mechanical engineers Syska & Hennessy. They conducted an experiment by placing recording thermometers in front of two windows, one with tinted glass and the other without, oriented as they would be in the building. After two weeks the thermometer behind the tinted glass had consistently recorded a temperature 5.5 to 8.5K (10 to 15 degrees Fahrenheit) lower.

This was adequate to convince Harrison that tinted glass without brise-soleil could moderate the heat and cold and justify its extra cost. With hindsight this appears a huge leap in logic. However, the internal environment did not rely on the tinted glass alone. The windows had venetian blinds on the inside and 4,000 of the new "Carrier Weathermaster" high velocity induction units beneath the sills.

This type of air conditioning system and location of terminal unit has three main advantages: 1) most heat gain and loss from the building are through the window and the location of the units compensates immediately with minimal effect on the room condition, 2) heating and cooling energy is transported around the building by water, a much more efficient medium than earlier systems that used air and, 3) much less vertical duct space is required as the main supply ducts operate at high velocity and only handle enough air to meet the minimum fresh air ventilation requirements. Horizontal ducts to the perimeter are concealed in ceiling voids formed by the now ubiquitous acoustic tiles. The offices also have the relatively generous floor to ceiling height of 2.85m (9'-6"). Despite problems with the curtain walling(19) and detractors such as Le Corbusier and an anonymous commentator cited by the Architectural Review who wrote "...air conditioning and venetian blinds are pitted against the powerful sun..," the combination of tinted glass, ventetian blinds and a high velocity perimeter induction unit system must have worked well. It was repeated on numerous buildings for the next twenty or thirty years.

Similar principles were adopted for the design of Lever House, completed in 1952, two years after the United Nations Building. Unlike the UN building it is totally curtain walled on all four sides and was one of the first to have sealed windows and an automated window cleaning gondola supported from hoist on a track at roof level. It only has 21 storeys which eliminates the need for intermediate plant rooms. The light, almost transparent appearance became very popular and led to similar buildings appearing in most western cities in the 1950s and 60s. Air conditioning in this building is fundamental to the design and the building could not operate without it. Lever House and the Equitable Building were probably the first office buildings where this applied and they were to be much copied.

Fig. 10 Lever House, 1952

These two buildings were seminal examples in introducing a concept that allowed architects to design sealed, transparent, buildings without, apparently sacrificing the internal environment. When this style was exported the architects did not always appear to understand the essential nature of air conditioning in this concept. This coupled with poor quality curtain walling helped create a poor image for this style of building. One of the earliest large developments after the war in London was the development of the Barbican area that had been extensively damaged by bombing. It included six office towers built in the style of Lever House(20).The development was closely controlled by the local authorities who set parameters for the appearance and size of each building. This included specifying curtain walling and a storey height of 3.3m. The buildings were naturally ventilated and these stipulations failed to recognise the significance, in terms of achieving a comfortably cool office environment ,of the greater storey height and air conditioning at Lever House. Unfortunately, this set a pattern that was followed in a number of developments in the early 1960s in London. Although it soon became apparent that buildings of this type need air conditioning, irrespective of geographical location, few of them were built with adequate storey height. The end result is that many of these buildings will be prematurely demolished which has already happened to one of the south Barbican towers.

AIR CONDITIONING IN LONDON

In the early to mid 1960s, when there was a boom in new air conditioned buildings in London. Induction unit systems were the most common but other types were used, for example, radiant cooling ceilings at the Shell Centre and "dual duct" in No. 1. Victoria Street.. At the time dual duct was considered as a "luxury" system and implicitly more expensive. Although high velocity induction units became most popular at this time they have characteristic problems. They include: the space necessary to house the terminal units and the high velocity ducts(at the perimeter of the building), the noise generated by the ejector nozzles, the risk of noise from leaks in the high velocity duct connections and the energy use of high velocity and pressure air supply systems. Some architects solved the problem of housing the ducts at the perimeter of the building by mounting them on the outside of the structure and creating a more sculpted form of facade.

THE ASCENT OF VAV

The concept of the induction unit is an internal "window box"(21) that provides ventilation, heating and cooling and replaces the radiator or heater usually sited beneath the window-sill. The location means that the units do not clash with partitions and with the typical 1.5m module one unit is normally installed every other bay. This standardises layout and makes it is easy to provide individual thermostatic control to cellular offices. Fan coil units and reverse cycle heat pumps can, and are, used in a similar manner. These terminal units provide adequate control of spaces up to around 6m or so deep. The interior zones of deeper plan offices, with lesser heat gains and losses, are usually air conditioned independently by various types of "all-air" systems.

In the mid to late 1960s a new "all-air" system concept was introduced(22), intended to provide air conditioning from the window wall to the core independent of depth and only supplemented by heating at the perimeter. It too used high velocity ducts developed for induction systems but, instead of adjusting the temperature of the air supplied to the space to meet changes in coling loads it varies the rate of air flow. As the supply air temperature is kept constant and the rate of air flow has to be adequate to meet the maximum for cooling and the minimum for ventilation the system can only handle a limited range of conditions. However, with the increasing use of permanent artificial lighting, better insulation and the increasing heat from machines designers found that the interior zones required year round cooling and the limited range of duties offered matched their requirements. Providing heating is sited at the outside wall to offset heat losses each entire floor plan independent of size could be considered as an "internal zone."

The system is called "Variable Air Volume"(VAV) and, at the time, appeared to have advantages over the constant flow systems used previously. The terminal units, "VAV boxes," are usually located in a ceiling void and incorporate some form of damper to regulate the airflow in response to the temperature sensor plus an automatic regulator to adjust for fluctuations in the supply air system caused by other controllers. The advantages include: a) the rate of air flow varies with the rate of cooling therefore, if less is required less energy is necessary for delivery and, b) as the maximum demand for cooling never coincides simultaneously in all spaces the maximum duty of the air handling plant and size of main ducts must be less and, c) an economy cycle can be incorporated to use outside air to providing cooling at the times when the temperature is appropriate.

One of the disadvantages of "all-air" systems such as VAV is the size of air handling plants and ducts and the resulting loss of floor area and building volume by comparison with "air and water" systems such as fan-coil. They use at least twice the floor space and need ceiling voids 30% deeper. The consequences on the height of a multi-storey building are obvious. The effect is often mitigated in tall buildings by installing air handling plants at each floor level which are only supplied with minimum fresh air. The consequence is that the benefits of the economy cycle are sacrificed. With this concept the main fresh air and floor air handling plants operate in tandem similar to the PSFS building.

Notwithstanding the limited range of cooling, complaints of inadequate ventilation and, the difficulties of commissioning and controlling, VAV systems became the dominant method of air conditioning offices in the 1980s. Major developments such as Broadgate (See figure 11.) and Canary Wharf were entirely conditioned by VAV.

Fig. 11. Broadgate Development

It appears that engineers were seduced by the simplicity and, apparent energy economies, Perhaps more importantly, for some unknown reason, the acronym VAV became synonymous with high quality air conditioning. Variations on the original concept were introduced to mitigate some of the implicit constraints and fans and secondary coils were added to the terminal units. Although this detracted from the simplicity of the concept it allowed engineers to overcome many of the initial problems of the early systems. VAV can now match any other system in terms of performance.

Improvements in the internal environment of air conditioned offices are not solely the results of improvements to the mechanical systems. Curtain wall technology has improved dramatically since the period of the1950s, when it was notorious for leaks and condensation. The high levels of insulation and integral solar control can now provide the "neutralising" effect at the outer skin of buildings to which Le Corbusier could only aspire in the 1920s.

Although VAV achieved dominance in new major buildings the space necessary to house the ducts, air handling plant and terminal units meant that it was impossible to fit the system into older buildings that had been designed without air conditioning or perimeter induction systems. In the 1970s, fan-coil units, that had been developed as long ago as the 1930s, had totally displaced perimeter induction units as the most popular choice for "window box type applications. One of the reasons was that they did not need the bulky high velocity ducts that had to be accommodated at the very edge of the building, another was the absence of the characteristic hiss of the nozzles. In addition, like VAV boxes, fan-coil units can conveniently be installed in ceiling voids and release valuable floor space beneath the windows.

COOL COMFORT - ACTIVE VERSUS PASSIVE

During the building boom of the 1980s, at the time when VAV air conditioning was the dominant method of air conditioning, some designers were looking at different solutions to the problem of providing cool comfort. Architects and engineers on projects such as Gateway Two in Basingstoke were re-exploring the passive techniques of maintaining a comfortable internal environment. The need to seal or keep the windows closed in "air conditioned" buildings was being challenged in buildings such as the Colognia Building in Cologne(23), the SAS building in Stockholm(24) and Dow(25) at Horgen near Zurich. The general objective is to combine the advantages of naturally ventilated buildings with those of air conditioned to provide greater comfort and less energy use. This concept of "air conditioned" naturally ventilated buildings has also been recently adopted in the UK(26). The common factor in these recent buildings has been the use of opening windows in high performance walls.

A post occupancy survey of buildings in the UK, built during the 1980s(27), concluded that "...to many people that occupy air conditioned buildings this service gives the greatest headache." The main problems were identified as a lack of thought at the design stage and poor commissioning during the customary rush at the end of the contract. Many larger occupiers expressed the view that "..poor air conditioning is worse than none at all."

This was, perversely, confirmed in a more recent survey(28), of five air conditioned and six naturally ventilated buildings that showed, in terms of comfort, there is little to choose. This survey concluded that the success of buildings depends more on the brief, the design process and control and response of the environmental systems than whether they are air conditioned or not. This implies that comfort in these buildings is not a matter of whether or not they are air conditioned but something more fundamental. The failings to provide cool comfort in many buildings, particularly those constructed in the early days of office air conditioning and curtain walling, were obvious both the fabric and the systems failed to perform. The situation is different now, we have gained considerable experience in what not to do what we must make certain is that we do not repeat these mistakes in the next generation of buildings.

CONCLUSIONS

In retrospect the impact of air conditioning on buildings can be seen to have two major effects. The first was the opportunity to design and construct buildings without the constraints of passive measures to maintain cool comfort. Frank Lloyd Wright grasped this opportunity in the Larkin building, overlaying active mechanical ventilation and cooling on what was fundamentally a passive structure. The passive features such as generous floor to ceiling height, high "thermal" mass walls and ceilings and recessed windows, no doubt contributed to the success of the comfortable environment. Quinan, in his thorough study of the building, says ""Heating and ventilation in the Larkin Building was as vital to its success as illumination." The building was surrounded on three sides by trains with coal burning engines pouring out black smuts, the last thing that the Larkin Company wanted soiling its correspondence selling expensive soap by mail order. Heating and ventilation, in the context that Quinan uses it, includes the cooling system. Had it not been installed the building might have suffered the same consequences as Le Corbusier's Salvation Army hostel. In the event the Larkin building was demolished in 1950. Nevertheless its spirit lives on in the many buildings that share its characteristics. It easy to trace the links between the building and the many recent air conditioned and non air conditioned successors that utilise the building and machine to create cool comfort.

The second major effect was the opportunity to introduce new materials and construction techniques in the, sometimes uncertain, knowledge that air conditioning will maintain a comfortable environment. The outer shells of buildings provide the primary barrier between the internal and external environments. The environmental systems, heating ventilating and cooling or air conditioning compensate for the adequacies or otherwise of he barrier. It is now difficult to distinguish whether poor curtain walls created an adverse view of air conditioning in the 1950s and 60s or whether the fault lay with inadequate air conditioning systems. The current cladding systems that evolved from these "experiments" now provide the level of isolation from the outside climate only aspired to by Le Corbusier with his neutralising wall concept. The downside of this technology is that it is cheaper to seal buildings with cladding than to provide opening windows, which means that they will mot probably remain air conditioned for their life irrespective whether or not it can be justified by future activities and energy costs.

Not all air conditioned buildings have been successful, many appear to have been designed on the principle of "short life, tight fit, high energy." However projects such as the Lloyds Building in London and the Bank of Hong Kong and Shanghai would not have left the drawing board without the knowledge that the internal climate could be created by air conditioning. The foolish conviction that air conditioning can provide comfort irrespective of the building shell has disappeared. The energy crises and changes of attitude now mean that naturally ventilated buildings can be viewed in the same "prestigious" class of building that was, for a while dominated by air conditioned buildings.

The time has now come when, quite often, designers are challenged with the task of recycling failed 1960/70s air conditioned buildings. The major problems are the constraints of limited floor to ceiling heights and inadequate shells. The cladding is relatively easy to replace but increasing the height is impossible. Surely we should insist when we are members of teams on new projects that we do not perpetuate the "short life, tight fit, high energy" philosophy apparent in so many of our previous attempts.

An apparent advantage of air conditioning is that less needs to be spent of the shell in terms of shading and opening windows. The history of air conditioning has shown that this is a short term concept. Despite the possible additional cost of a passive shell, the life cycle cost of such a building is most likely to be less irrespective of whether the building is air conditioned or not. It is easy to change a passive building into an air conditioned one, the reverse is difficult if not impossible and very expensive.

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