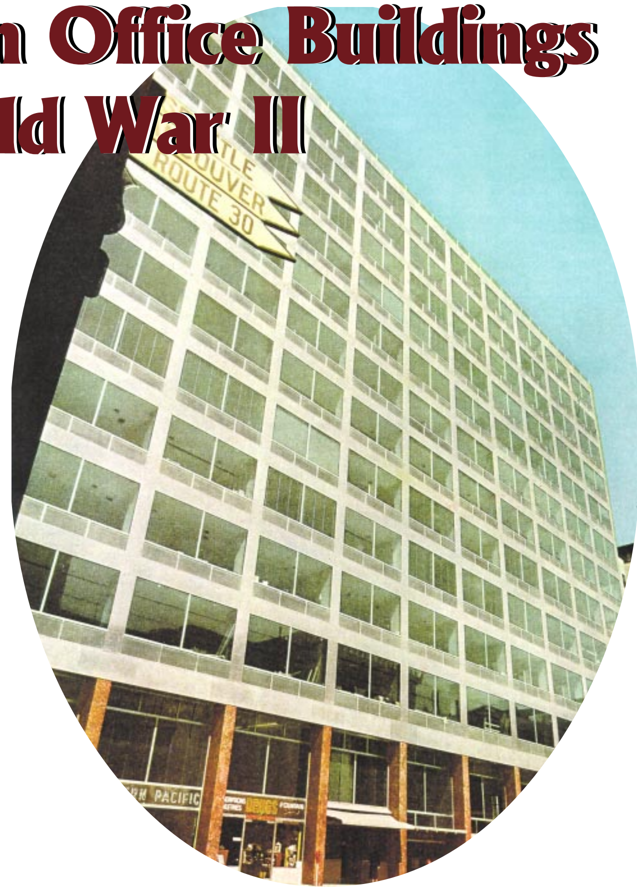
Air Conditioning in Office Buildings After World War II



Front elevation of the Equitable Building in Portland, Ore.[8] The building is considered to be the prototype for the modern fully air-conditioned building.

The First Century of Air Conditioning

This is the eighth article in our special series to commemorate a century of innovation in the HVAC&R arts and sciences.

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This is the second of two articles reviewing the evolution of modern office building design and the impact of air conditioning. The first article focused on the period from the mid-19th century, when offices emerged as a distinct category of building, to the advent of fully air-conditioned office buildings in the 1930s.

As the economy in the United States recovered from the Depression, in the late 1930s, air-conditioning equipment sales doubled in one year, rising to more than $30 million in the first five months of 1937.[1] All of the major manufacturers—General Electric, Frigidaire, Carrier, York, Westinghouse etc.—produced room air conditioners which mostly were installed in offices. However, despite the availability of these room conditioners, and fan coil units which had been patented by Reuben Trane in 1932,[2] the technology for centralized large building air conditioning hardly had changed from the earliest installations by Alfred Wolff and Willis Carrier. The technology for terminal unit systems was known and published,[3,4] but hardly applied.

Most of the air-conditioned buildings constructed before World War II had "all air" systems. The large amount of space sacrificed to vertical ducts was a major disincentive to property developers attempting to maximize their profit on every square foot. The era of the deep open planned office had not arrived.

Air Conditioning and Curtain Walling

In the absence of new projects during the war moratorium on civilian buildings, one of the leading architectural magazines, *Architectural Forum*, ran a special issue on post-war trends.[5] The editor, Howard Myers, invited a number of leading architects including Louis Kahn, William Lescaze, Mies van der Rohe and a lesser known Italian architect from Portland, Ore., Pietro Belluschi, to produce designs for a range of projects that might be built in a medium sized town after war-time building restrictions were lifted. Myers stipulated that the architects' design "show an advanced but not stratospheric" approach to planning construction and equipment and that they draw upon technology that was currently available but not yet in common use.

Myers selected Belluschi to produce an office building design. Belluschi wrote, "Our assumptions were affected by the peculiar circumstances found in our northwest region—cheap power and a tremendously expanded production of light metals for war use, which will beg for utilization after the emergency." Apparently he intended to air condition the building using aluminum extensively for cladding, wall-panel frames, external air inlets, internal louver blinds and even as trays for ceiling tiles. The extent of the use of aluminum is shown in the cross section of his design in *Figure 1*. It also shows his proposals for maintaining internal comfort with unit air conditioners, individual local air inlets, and radiant heating panels

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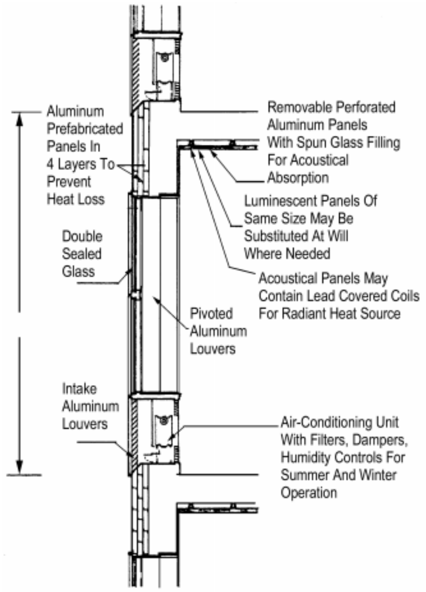

Figure 1: Belluschi's 1943 design study for an office building in "194X."

in the ceiling. The large windows are complete with aluminum louver blinds.

The Equitable Building

Belluschi put his ideas into practice before the war ended. The Equitable Savings and Loan Association intended to build a new headquarters in Portland.[7] Although superficially the design for the building was similar to the *Forum* project, Belluschi introduced a number of significant changes that impacted the internal environment as much as the appearance.

The building was heralded by *Architectural Forum*[8] as the first and long overdue "crystal and metal tower" and one of its most spectacular aspects is "its huge areas of sea green glass." The glass was sealed double-glazing with the outer pane made of heat absorbing glass that provided a 40% reduction in solar transmission.

Belluschi had satisfied himself that the solar-treated glazing would not only reduce the solar heat load but also reduce sky glare to the point where blinds or shades would not be needed for comfort. Apparently, "some of the tenants expressed alarm at the lack of shading, but after several months of satisfactory conditions few of them had installed blinds."

The mechanical engineer, J. Donald Kroeker, was as innovative as the architect. The building was one of the first to be entirely heated and cooled using water from wells via a heat pump. The air-conditioning systems were controlled automatically and local air-handling plants installed on each floor had separate ducts serving different faces of the building and interior zones and included the option of 100% outdoor air. Kroeker claimed a reduction in operating costs of between 10% and 25% in comparison with heating and ventilating only.

The building, now called the Commonwealth Building, is the prototype for the modern fully air-conditioned building. The air-conditioning system was installed to counteract the heat gain from the large sealed windows without the need for blinds or shading. Ultimately, this may have been an unfortunate precedent in terms of energy and the environment. However, the building and systems have been monitored closely since 1948 and are still performing well and economically.[10,11] Despite its location and lack of publicity, it is a seminal building in the development of air-conditioned offices.

United Nations Building

The United Nations Building in New York was the first major international building to be constructed after the war. A multinational advisory committee was established for the design of the building. It was composed of a number of leading architects, including Le Corbusier. The director of planning and lead architect was Wallace K. Harrison who helped design tall buildings such as Rockerfeller Center before the war.[12]

During the development of the scheme, Harrison was involved in a number of conflicts with Le Corbusier, who allegedly claimed credit for the design concept. One such argument involved protection of the offices in the Secretariat (Tower) Building against excessive solar heat gain and glare. Le Corbusier had preferred stone facades but the board preferred to maximize sun and natural daylight using overall glazing. They decided this could be achieved best with curtain walling, even though at the time it was an unusual solution for a skyscraper.

The Equitable Building was the only example of a continuous glazed curtain wall in the country and "even in those energy rich days this much glass raised the question of heat gain and loss." They considered four different glazing options in conjunction with internal venetian blinds. These included single and double-glazing with and without tinted glass.

Le Corbusier thought that the tower building should be protected from the sun by brise-soleil.[12] Brise-soleil eventually were eliminated because snow and ice collecting on them in winter would create a hazard.

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 of 5.5°K to 8.5°K (10°F to 15°F) lower. This convinced Harrison that tinted glass without brise-soleil could moderate the heat and cold and justify its extra cost.

In hindsight this appears to be a huge leap in logic. However, the internal environment did not rely on 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. Up to the time when these units became available, large building air-conditioning systems were almost invariably all-air and had correspondingly large ducts.

Carrier recognized the problem in the 1920s and decided that high velocity air was the answer.[12] He did not pursue it at

Figure 2: Interior view of a typical office in the Equitable Building.[9]

the time but developed a range of room terminal units intended to reduce the total volume of air by supplying primary air at a lower temperature and mixing it with room air.

It was not until 1937 that he developed the idea further. Patents were applied for and the first installations were completed in 1940, only months before the United States entered the war and new building construction virtually ceased.

The application of this type of "air and water" terminal unit method of air conditioning was another important advance. The air and water induction unit air-conditioning system had three main advantages over the all-air systems at the time:

- Most heat gain and loss from the building is through the window and the under-sill location of the units compensates with minimal effect on the room condition.
- Heating and cooling energy is transported around the building by water, a much more efficient medium than earlier systems that used air.
- Considerably 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.

Figure 2 shows the location of the unit beneath the window and how the horizontal ducts connecting to the units were concealed, on the floor below, in ceiling voids formed by the now ubiquitous, acoustic ceiling tiles.

Despite problems with the curtain walling,[14] the combination of tinted glass, venetian blinds and a high velocity perimeter induction unit system must have worked well, as it was repeated on numerous buildings for the next 20 or 30 years. Peculiarly though, for an air-conditioned building, the windows in the tower were operable although no reason seems to have been recorded why they did not follow the pattern set by Belluschi.

Lever House

Similar principles were adopted for the design of Lever House,[15] completed in 1952, two years after the U.N. Building. Unlike the U.N. building, it is totally curtain walled on all four sides and was one of the first to have sealed windows and

Figure 3: Lever House, 1952.[16]

an automated window-cleaning gondola supported from hoist on a track at roof level. It has only 21 stories that with the use of high velocity air ducts eliminate the need for intermediate plant rooms.

The light, almost transparent appearance became very popular and led to similar buildings appearing in most U.S. western cities in the 1950s and 60s. Air conditioning in this building is so fundamental to the design that the building could not operate without it. Lever House and the Equitable Building were two of the first office buildings where this applied.

Exporting the Concept

These buildings allowed architects to design sealed, transparent buildings without apparently sacrificing the internal environment. When this style was used elsewhere, the architects did not always appear to understand the essential nature of air conditioning in this concept. This problem coupled with the failures of early curtain walling helped create a poor image for this style of building.

One of the earliest major post-war construction developments in the U.K. was the Barbican area in London that had been extensively damaged by bombing. The plans included six office towers built in the style of Lever House.[17] The local authorities in London set parameters for the appearance and size of each building. This included specifying curtain walling and a story height of 3.3 m (11 ft). At the time, air conditioning was rarely used in London offices, so the buildings were naturally ventilated using operable windows. The specification failed to recognize the significance of air conditioning in role model buildings such as Lever House—opening windows was a poor substitute.

Unfortunately, the sleek modern appearance of these buildings set a pattern that was followed in a number of developments in the early 1960s in London and the rest of the western world. Although it soon became apparent that buildings of this type need air conditioning, irrespective of geographical location, few of them were built with adequate story height. As a result, the buildings do not provide comfortable working conditions and they also lack the flexibility for change. Many of these buildings will be prematurely demolished, which has already happened in London.

Air-conditioned offices eventually arrived in London in the 1960s. There was a boom in new office buildings, and following the poor performance of the Lever House clones, many of them were air-conditioned. Following patterns set in the U.S., induction unit systems were the most common. Dual duct systems also were used on a few buildings but were found to be expensive. As experience grew with high velocity induction units, engineers became aware of the following shortcomings:

- The amount of 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.
- The energy use of high velocity/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. Eventually the popularity of induction units in Europe was displaced by fan-coil units and variable-air-volume systems (VAV).

The Ascent of VAV

The concept of the induction unit is an indoor "window box" that provides ventilation, heating and cooling and replaces the heater beneath the windowsill in non-air-conditioned buildings. As there is usually one unit per window or every other window module, the units do not clash with partitions. This standardizes layout and makes it is easy to provide individual thermostatic control to cellular offices. Fan coil units and reverse cycle heat pumps are used in a similar manner. These terminal units provide adequate control of spaces up to about 6 m (20 ft) or so deep. The interior zones of deeper plan offices, with lesser heat gains and losses, were 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,[18] which was intended to provide air conditioning from the window wall to the core, independent of depth and only supplemented by heating at the perimeter. It also used high-velocity ducts similar to induction systems but varied the rate of airflow instead of adjusting the temperature of the air supplied to the space to meet changes in cooling loads. As the supply air temperature is constant and the rate of airflow must 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. If 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."

At the time, VAV appeared to have considerable advantages over the constant flow systems used previously, including:

- The airflow rate varies with the rate of cooling therefore, if less airflow is required less energy is necessary for delivery.

Figure 4: Broadgate development, London.

- 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.
- An economy cycle can be incorporated to use outside air to provide 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. VAV loses about twice the floor space for vertical ducts and needs ceiling voids 30% deeper. The consequences on the height of a multistory building are obvious. The effect often is mitigated in tall buildings by installing air-handling plants at each floor supplied with only the minimum rate of fresh air by other means. This means that the benefits of the economy cycle are sacrificed. With this concept of VAV, the main fresh air and floor air-handling plants operate in tandem similar to the PSFS building described in the previous article.

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 1970s and 80s. Major office building developments in other cities were often entirely conditioned by VAV. For example, the two largest developments in London, Broadgate (see *Figure 4*) and Canary Wharf, were built on the "shell and core" principal with one VAV air-handling plant per floor (an idea imported from the United States).

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.

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 1950s, when it was notorious for leaks and condensation. The high levels of insulation and integral solar control can now provide the neutralizing effect at the outer skin of buildings that Le Corbusier only imagined in the 1920s.

Although VAV achieved dominance in new major buildings, the space necessary to house the equipment meant that it was impossible to fit the system into older buildings designed without air conditioning or perimeter induction systems. In the 1970s, fan-coil units, developed as long ago as the 1930s, had displaced perimeter induction units as the most popular choice for window box type applications. The units did not need the bulky high velocity ducts that had to be accommodated at the very edge of the building and did not have the characteristic hiss of the nozzles.

Alternatives to Full Air Conditioning

During the building boom of the 1980s, at the time when VAV air conditioning was the dominant method, some designers were looking at different cooling solutions. Architects and engineers on projects such as Gateway Two in Basingstoke, England explored maintaining comfortable internal environments using natural ventilation alone. This building was completed in 1983. It is located in a temperate climate and shaded from excess solar gain. The concept of an atrium is used to provide ventilation and light naturally, see *Figure 5*. False ceilings were omitted from the offices and the thermal mass of the structure was used to limit the rise and swing in internal temperature. The performance of the building was closely monitored[19] and the results established the principle, for the United Kingdom climate, that prestigious buildings need not necessarily be air conditioned.

The need to seal or keep windows closed in air-conditioned buildings was challenged by designers in buildings such as the Colognia Building in Cologne,[20] the SAS building in Stockholm[21] and

Dow European headquarters near Zurich.[22] The general principle of the systems in these buildings is to combine the advantages of naturally ventilated buildings with those of air-conditioned, and provide greater comfort for less energy use. This concept of "air-conditioned" naturally ventilated buildings is gaining popularity in the U.K.[23] Common factors in these buildings includes:

- The use of opening windows in high performance walls.
- No recirculation air.
- Passive cooling (i.e., chilled beams and chilled ceilings).
- Local control by occupants.
- Clear as opposed to tinted/reflective glazing.
- Solar shading.

The technique of using natural ventilation and air conditioning in the same building, but at different times of year, is known as "mixed mode."[24] It is an alternative strategy that attempts to combine the best features of natural and mechanical systems. The buildings and engineering systems are integrated and intended to operate in the natural mode whenever possible, to minimize energy use. Mechanical systems are used only at peak conditions at the extremes of external temperatures. An example of a mixed mode building is shown in *Figure 6*.

This is the headquarters building for a credit card company in Northampton, England and it uses passive cooling from overnight ventilation and a cooling pond for most of the year and ammonia chillers under extreme conditions. The cooling pond supplies naturally cooled water to chilled beams up to around 20°C (68°F). When the temperature exceeds this, the pond is used to reject heat from the chiller condensers.

Alternative techniques, that respond to climate and geographic location rather than follow the U.S. model, are under development. These techniques are driven by the awareness of the potential environmental impact of air conditioning.

Figure 5: Atrium at Gateway House.

Conclusions

The impact of air conditioning on office buildings has had two major effects. First, is the opportunity to design and construct buildings without the constraints of passive measures to maintain cool comfort. The second 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 compensate for the inadequacies or otherwise of the 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. The downside of this technology is that it is cheaper to build lightweight buildings and seal them with cladding than to provide passive means of control such as exposed mass and operable windows. This means buildings will most probably remain air conditioned for their life irrespective of whether or not cooling can be provided by natural means and the impact of full air conditioning on the environment.

Figure 6: Mixed mode building showing chilled beams.

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