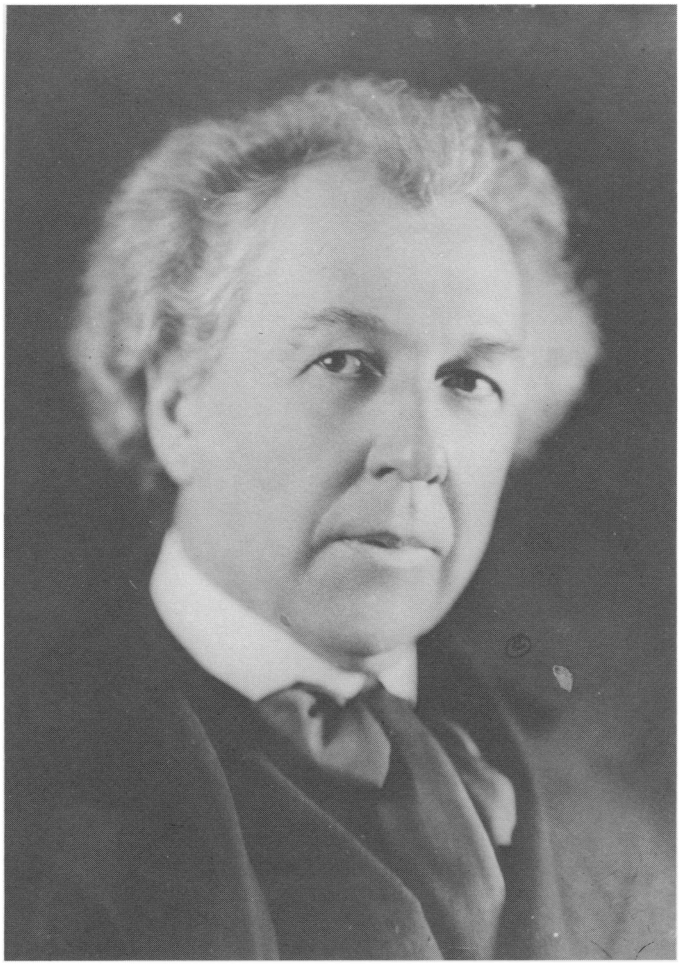


Frank Lloyd Wright (DeLonge Studio, Madison WI, courtesy of State Historical Society of Wisconsin)

HEATING AND COOLING ROBIE HOUSE

Justin Estoque

Adapting modern heating and cooling systems to Frank Lloyd Wright's Robie House required a respect for Wright's original heating and cooling systems. In designing the Robie House, Wright consciously sought to enhance human comfort. In that sense, the architecture itself was an expression of the architect's concern for the comfort of the occupants.

Eighty years ago, when the house was designed, most architects and engineers had only a rudimentary understanding of natural ventilation as a cooling mechanism. Although Wright's design surpassed contemporary standards, the house does not meet the needs of the current occupants of the building: the house is no longer a residence, and the availability of air conditioning has raised modern comfort standards.

It was our task to understand how the building worked when it was originally designed, to examine its performance today, and to adapt the mechanical systems to the needs of the current occupants — all without destroying the integrity of the structure.

The owner of the building, the University of Chicago, and the occupant, the Office of University Alumni Affairs, requested recommendations for adapting the Robie House ventilation and cooling systems to accommodate present-day office functions without compromising the building's historic integrity. The University recognized that the existing window air conditioners detracted from the building's appearance. Natural ventilation was preferred, as long as it could meet the needs of a modern office. This option seemed especially attractive, given the natural-cooling design features mentioned by Frank Lloyd Wright scholars and confirmed by our study. But if central cooling was necessary for the hottest summer months, we did not know what modifications would be required for fans, ductwork, and equipment.

To better understand how the house was originally supposed to function, we compared Robie House thermal comfort to historical ventilation standards and modern comfort standards. We found that the Robie House was superior to comparable Chicago houses for summer comfort. When the Robie House was built, ventilation was not considered a comfort issue as much as it was a wintertime health issue. Wright, however, had recognized the thermal and psychological advantages that natural ventilation could provide, and he incorporated many design features to improve ventilation: increased window area; open, flowing spaces permitting better air movement; and properly sized overhangs. Ceiling plenum ventilation and building orientation also helped in this regard.

Even with these ameneties, the Robie House fell short of modern comfort standards. Computer simulations show some

The south facade of Robie house is shaded by overhanging eaves in summer. Cooling breezes are drawn through windows. The house was designed for the occupants' comfort. (Richard Nickel, courtesy of Richard Nickel Committee)

room temperatures higher than 78° F for more than 800 occupied hours per year and higher than 90° F for more than 600 occupied hours per year. This was due in part to conferences and dinners which would generate heat.

Based on these results, natural ventilation, although consistent with Wright's design philosophy, was insufficient to meet the comfort requirements of its current occupants. We recommended that both natural ventilation and refrigerated cooling be used. Natural ventilation would be achieved by repairing the historic windows and doors, many of which are fragile and permanently shut to forestall further deterioration. Though estimated to cost $35,000, the repair of the windows would address both historic preservation and comfort needs for much of the year. Refrigerated cooling could then be installed to handle peak cooling loads and provide more stable climate control.

To understand how natural ventilation, modern cooling, and heating could be adapted to the site, we began with a thorough analysis of the original system. We then developed a comprehensive monitoring program to analyze present use. Based on this information, we found that it was possible to adapt the heating system to provide cooling as well. The adaptation required very slight changes in the building fabric.

Justin Estoque is with Burt Hill Kosar Rittelmann Associates, Washington DC.
The author wishes to acknowledge Syed Faruq Ahmed, Margaret Maliszewski, and David Linamen as contributing authors. Funding was provided by the U.S. Department of Energy and the National Endowment for the Arts through IDEA, Inc.

Sensitivity to the building fabric and a careful pre-design study made it possible to design a cooling system compatible with Frank Lloyd Wright's Robie House.

Robie House History

An Architectural Landmark. Built in 1909, the Robie House is the culmination of those unique architectural qualities in Wright's design which had been growing and maturing since the 1890's: the building form based on interlocking masses of rectangular blocks; low, horizontal rooflines with long, cantilevered overhangs; the low, broad chimney and central outdoors seen through bands of windows. The house is a bold structure of brick masonry and concrete whose strong planes, hovering roofs, and projecting balconies seem to float, with nothing in between to hold them apart but one strong vertical element — the chimney mass. Its form has been described as a great ship complete with prow, funnel, and decks, whose crisp brickwork and geometric outlines have been softened with "hanging gardens" emerging from earth pockets in terrace walls. The house was designated the first United States Registered National Historic Landmark in the City of Chicago.

The Robie House floor plan is significantly different from other residences of its time. Rather than opening directly onto the street, the entry is tucked away on the ground level behind the dominant south facade of the building. On this level, beside the north foyer, are a billiard room to the west, a children's playroom with a prow-shaped end to the east, and an attached three-car garage, one of the first ever provided for a Chicago residence.

The most famous rooms are the living and dining rooms located on the second level. Both rooms have prow-shaped ends and are separated by a large, brick fireplace, pierced in the center to enhance the long, dramatic perspective from one end of the house to the other. Patterned oak screens in the ceiling filter light from recessed electric fixtures supplemented with light globes held aloft by wooden spacers. A sweeping rhythm of French doors on the south and half-windows on the north admit light and air, while the stained glass set in zinc channels provides enough privacy to dispense with heavy, dark drapes. Radiators and fan-coil units are recessed beneath wooden grilles or under the floor so that warm air rises along the cold windows and walls.

To help preserve the house in spite of heavy use and limited funding, planning and establishing work priorities was essential.

In a setback to the north, a guest bedroom and bath open off a short hall adjoining the kitchen. To the east of the kitchen over the three-car garage are the servants' quarters. In this part of the house, as on the third floor, the ceilings are vaulted, following the lines of the roof above.

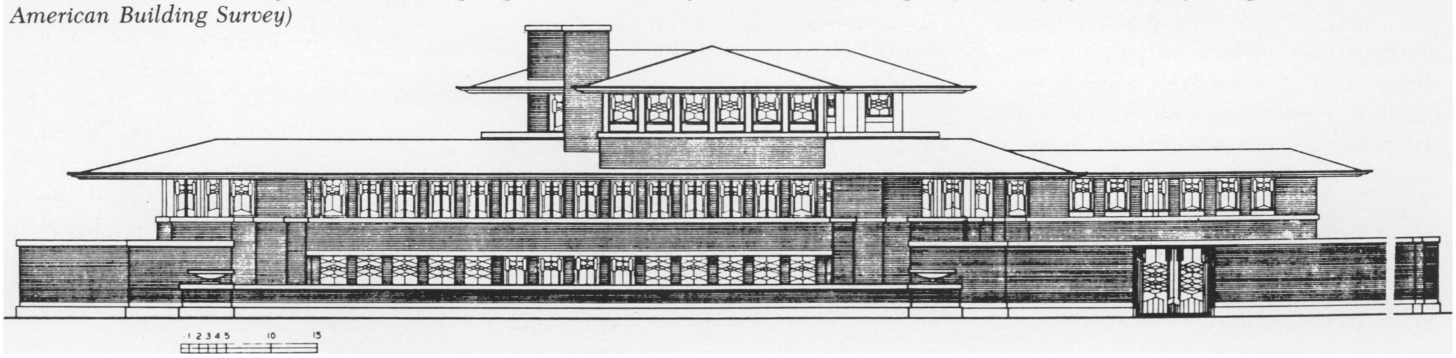
The top floor has the master bedroom, bath, and dressing room, with a small sunning balcony to the west. The two children's bedrooms with adjoining bath are also located on this floor. There is no attic or basement.

Present Use

The house has been adapted today to serve as office space. The offices are open during regular business hours; but, recognizing the building's place in American architecture, the Office allows tours in the foyer, living room, dining room, and adjacent outdoor areas. Eight to ten thousand people per year tour the house, and receptions or dinners are held up to 20 times a month. Use of the house will probably intensify as more groups learn about its availability.

To help preserve the house in spite of its heavy use and limited renovation funding, the University Office of Physical Planning and Construction established priorities for restoration funding in upcoming years. Funds raised in the immediate future will be directed toward repair of windows, doors and metal roof components. Air conditioning, heating and roof insulation have been designated a third priority by the University's consulting architect, John Vinci. However, planning for the eventual overhaul of these systems and assuring that their renewal does not damage the integrity of the house were the reasons for our involvement in the project at an early stage.

Low, horizontal roof lines with cantilevered overhangs are seen on this elevation of the south facade. Prow-shaped living room is on the second level to the left, and attached garage and servants' quarters are to the right. (Courtesy of Library of Congress, Historic American Building Survey)



Comfort Control in 1900

In 1900, the ventilation of buildings was considered primarily a health issue.

> Most civilized men and women are unwilling to put on underclothing that has just been taken off by another person, or to put into their mouths articles of food or drink that have recently been in other people's mouths, but they take, without hesitation, into their lungs air that has just come from other people's mouths and lungs, or from close contact with their soiled clothing or bodies.[1]

Engineering guidelines were written by medical doctors or surgeons known as sanitary engineers. Many of them deplored the ignorance of mechanical engineers, pushing vigorously for sanitation-based ventilation standards to be included in engineering textbooks. The first ASHRAE guides were not published until about 1920.

Adequate ventilation as a health concern was considered more difficult to achieve in the winter than in the summer, resulting from the need to keep windows and doors closed during the heating season:

> While it may be required in some cases chiefly, or exclusively, to remove watery vapor, as in the drying rooms of a factory, or to keep an uninhabited room free from dampness, or to remove offensive or dangerous gases or foul odors generated by either natural or manufacturing processes, it is most usually employed to dilute and remove the products of exhalation and respiration of living animals, especially of man, and the products of combustion due to heating and illuminating apparatus, and to prevent the temperature of a room from rising above the degree which is requisite to secure comfort and health.[2]

The common method for determining acceptable rates of ventilation was based on diluting the concentration of these noxious gases to an acceptable standard.[3] Exhalation rates were examined in the 1800's to determine increases in "carbonic acid gas" (carbon dioxide) resulting from various numbers of people confined within an enclosed space. In the second half of the nineteenth century, sick individuals were thought to exhale 4 to 12 times as much carbonic acid and contaminated "watery vapor" and therefore required higher rates of ventilation.[4] Even after 1900, the reasons for adequate ventilation were still poorly understood, as evidenced by Konrad Meier, a New York heating consultant, in his *Reflections on Heating and Ventilating Engineering* (1904)[5]:

> . . .excessive amount of vapour of water, sickly odours from respiratory organs, unclean teeth, perspiration, untidy clothing,. . .stuffy air from dusty carpets and draperies, and many other factors that may combine, will in most cases cause greater discomfort and greater ill-health.[6]

Thus, ventilation standards, if followed, were based on reasonable guesses at best and Victorian imagination at worst.

Although ventilation standards may have been used in the design of large buildings and assembly halls, this level of rigor rarely, if ever, was used in the design of residences; heating was considered a more complex and important problem. For ventilating single-family dwellings, fireplaces were considered to induce ample ventilation in the winter, and if fireplaces were not available, the equivalent area of exhaust flue (called aspirating chimneys) or attic exhaust fans would suffice. In these cases, air was assumed to expand and rise as it was heated, thereby flowing naturally out of the flue or expelled by the fan and replaced by fresh air at the furnace or living space. A primary design requirement was to prevent drafts of cold air entering directly into the living spaces. In the summer, opening the windows and doors was considered sufficient. No turn-of-the-century references related window area to health or comfort conditions.

Besides carbonic acid, dampness was also considered an environmental condition to avoid. Frank Lloyd Wright himself raised the conventional basement functions to the ground level to avoid the dark damp conditions found there. One of the design tenets he identified with his Prairie School philosophy was to ". . .get the unwholesome basement up out of the ground."[7]

Just north of the fireplace, the camera looks west toward the living room. Stained glass windows provided privacy, light, and ventilation. (Office of Public Relations, University of Chicago)

The dampness and other foul gases associated with basements discouraged the use of basements as a source of ventilation air.

> Sometimes it is taken directly from the cellar itself, in which case it is almost sure to be contaminated with gases escaping from the furnace door, while the cellar itself contains decaying vegetables, slop buckets, and perhaps an empty bell trap, giving free communication with the sewer. . .The fresh-air supply should not be brought in through an underground duct without taking special precautions to have it air-tight, and it should not pass across or near a drain or sewer.[8]

Architects usually left the job of providing ventilation air to the furnace installer who often chose a source based on the least cost and inconvenience. There was no return to the furnace; supply was 100% outside air. In larger buildings which required the sizing of flues and registers, more attention was paid to the source and rates of ventilation. Recommended rates ranged from 30 cfm/person (office and dining) to 60 cfm/person (hospitals, assembly halls, and barracks) — much higher than the 5 to 20 cfm/person usually used during the present day.[9]

With no air conditioners, cooling standards did not exist. Although winter indoor temperatures of 68° F or 70° F were considered comfortable, occupants lived with whatever level summer temperatures happened to reach.

The level of sophistication, even among professionals, was not high. The recommendations made by Billings are typical design guidelines for residential installations.

> 1. Position and size the registers to achieve sufficient air flow without causing drafts. Ninety feet per minute should be maximum. Perforated floors in assembly rooms should be at least 100 square inches per occupant; at the ceiling, however, 30 square inches per occupant with a fan is sufficient.
> 2. Fresh air registers must not be placed below foul air registers (to avoid short circuiting).
> 3. Flues small enough to embed in ordinary interior partitions are insufficient in size, except for residential use.
> 4. Do not place fresh air registers flush with the floor level (to avoid collecting dirt and dust).
> 5. In economical dwellings, centralize the heating apparatus, keeping fresh air flues within inner walls. Transfer grilles to upper floors can be placed under or near windows.
> 6. In residences, when fresh air registers are placed near the ceiling, and foul air registers near the floor, heat air to a higher temperature than required (due to the stratification). If opposite, enlarge grilles sufficiently to prevent disagreeable currents.
> 7. In dwellings with rooms having windows on one wall only, place fresh warm air openings on an inner wall and foul air registers on the same wall at a lower level. This will induce air flow from the warm air opening, across the ceiling, down in front of the window, and back along the floor to the foul air register.[10]

These recommendations allude to the importance of circulating heated air and preventing stratification, and show how a building or room "works." The Chicago building code made more specific recommendations for the placement of openings, suggesting that winter and summertime operation do not differ when fresh air is admitted at the lower level:

> . . .the inlets may be in the floor, in risers of platforms, in sides of walls near the floor, in stationary desks, and in front of stationary benches. . . The outlets may be in the cornice or ceiling or side of walls near the ceiling. This method requires no change with seasons — the fresh air in summer entering the same way that it does in winter. . .
> Where windows are available, and so placed that currents pass through the room, no provision need be made. . . for summer ventilation except when there is an object to keep them closed to exclude noise and dirt.[11]

The last quarter of the 19th century marked a period of rebuilding for Chicago. The catastrophic Chicago Fire of 1871 led public officials to make fireproof construction a major component of the building code. Building materials were soon upgraded to guard against another city-wide fire. Brick and stone were substituted for wood in both new and existing buildings. Frederick Robie himself insisted on the latest in fireproof construction. One side effect of this change in building materials was that the heavier materials made for cooler interior environments; but, they also created colder walls and floors in the winter.

Architectural styles that were popular at the time, such as Romanesque Revival and Queen Anne, were based on both wood and masonry construction. Glass panes were becoming larger, and the popular double-hung windows started incorporating single panes of heavy glass instead of the many small panes used in earlier window designs. Casement windows, which admit more air, were not popular on Prairie Avenue and in other fashionable neighborhoods of Chicago, although these and other elements of the Robie House had historic precedent (e.g., the grouped casement windows of the Tudor Style and the wide, overhanging eaves and hipped roof of the Italian Renaissance).

Our review of houses built during the late 1800's reveals that traditional Chicago residences used basements for habitable purposes, such as kitchens and their supporting services, presumably because these were heat-generating functions. Attics with dormers served as servants' quarters, presumably because these were the hottest and least convenient rooms of the house. Ground levels contained several large rooms — sitting rooms, living rooms, dining rooms, and parlors — with large foyers leading from a central entry which in turn led to a central stair.

This organization of spaces around a centralized circulation plan and their vertical arrangement was especially suited for the heating systems of the times; basement furnaces from which hot air rose through floor grilles, or steam systems where condensate returned to the boiler by gravity. On the other hand, natural ventilation was relatively difficult since most rooms only had windows on one wall, although some air movement was induced from floor to floor by opening dormer windows in the attic and admitting fresh air at the ground level.

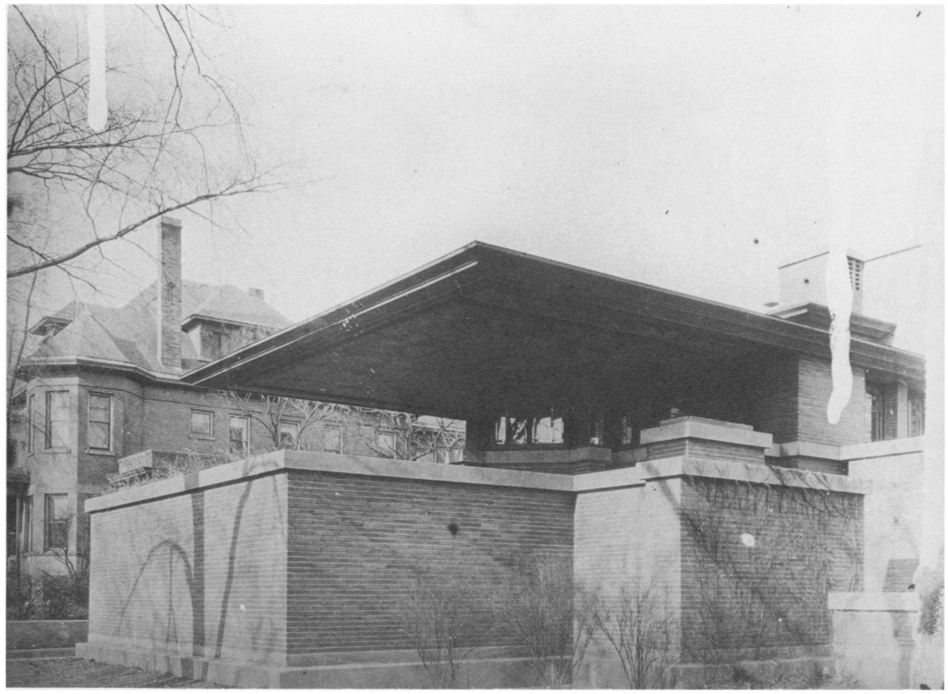
Wright's Changes

The preceding review describes the conventional residential building standards from which Wright departed. In some cases, the departure was made intentionally to improve occupant summer comfort; in others, the benefits were incidental. Other features of the house may have been common practice.

One intentional improvement was the elimination of hot, stuffy attics; in fact, Wright described them as quarters "for 'help' to swelter in" and dormers as places ". . .to let 'help' poke heads out of the attic for air."[12] Instead, he substituted the chimney to collect and expel hot air:

> . . .The gently-sloping roofs, grateful to the Prairie, do not leave large air-spaces above the rooms, and so the chimney has grown in dimensions and importance, and in hot weather ventilates at the high part of the circulating air-space beneath the roofs, the fresh air entering beneath the eaves through openings easily closed in winter.[13]

Wright also eliminated the basement due to its perceived unwholesome dampness and lack of windows, but in doing so, sacrificed its coolness.



Contrasts between the central-floor-plan house shown in the background and Wright's horizontal Robie house show what a profound effect modern radiant heating had on architectural design. (State Historical Society of Wisconsin)

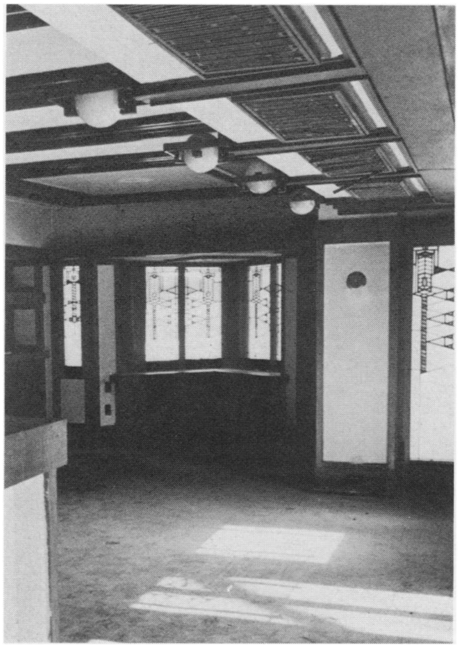
The result of removing the top story (and the basement) was a greater extension of living spaces over the lot which permitted more exterior window area. It also required more open, free-flowing living spaces if interior rooms were to have light, air, and view. Such design features complement Wright's Prairie Architecture with its low, horizontal buildings opening to the prairie. And the architecture itself was made possible by the use of modern heating systems which could better distribute heat than could their predecessors, as Wright himself explains:

> Another modern opportunity is afforded by our effective system of hot-water heating. By this means the forms of buildings may be more completely articulated, with light and air on several sides. By keeping the ceilings low the walls may be opened with a series of windows to the outer air, the flowers and trees, the prospects, and one may live as comfortably as formerly, less shut in. . . it is also possible to spread the buildings, which once in our climate of extremes were a compact box cut into compartments, into a more organic expression, making a house in a garden or the country the delightful thing in relation to either or both, that imagination would have it.[14]

Based on this statement, Reyner Banham ascribes Wright credit in the former's *Architecture of the Well-Tempered Environment*[15] for being one of the few to utilize the freedom in architectural form made possible by new heating technologies. But as form is inextricably integrated with heating, ventilation, and light in the characteristically organic Prairie School philosophy, the Robie House provides environmental amenities not found in its more traditional neighbors. These are summarized as follows:

Extent of operable doors and windows. On the second floor, the glazed area is so extensive that Frank Lloyd Wright referred to the walls as "light screens." This was a dramatic departure from homes of the day which he described as "overdressed wood home walls [which] had, cut in them...big holes for the big cat and little holes for the little cat to get in and out or for ulterior purposes of light and air."

In the living and dining rooms, close to 75% of the exterior wall could be opened to the outside compared with the more typical 20%. Furthermore, Wright insisted on using the outswinging casement windows versus ubiquitous "guillotine" (i.e., double-hung) windows. Not only did they allow 100% of the window area to be opened, but they have been shown (in modern-day experiments) to induce or divert greater air circulation near the window.



Wright's integration of lighting, ventilation, and ceiling finish trim is shown above. (Virginia Weissman Photo, Office of Public Relations, University of Chicago.)

Open floor plan allowing free movement of air. As discussed previously, typical residential design of the time in Oak Park produced boxy, compact homes where cubicle-like living spaces were organized around stairs and corridors. The Robie House's free-flowing interior circulation and punctured fireplace maximizes the circulation of fresh air, while its spread-out, extended floor plan permits extensive exterior window area.

Properly sized overhangs. Wright frequently mentions the horizontal line as the line of domesticity, evocative of the prairie. The horizontal roof line with its long east and west overhangs and relatively short south overhang illustrates this ideal, but it is also correct for proper shading. The east and west building faces are protected from low morning and afternoon sun angles, and on the south, the shorter overhang is sufficient to shade the glass from the high noon sun. Reyner Banham[16] mentions that the south overhang is the perfect length to shade the glass doors during the summer solstice. The shadow line angle from the actual sun position is 72° versus the angle from the actual overhang of 66° (calculated from the blueprints), but this is a minor difference in light of construction deviations and is more appropriate anyway for the heating and cooling loads in Chicago.

Other Features

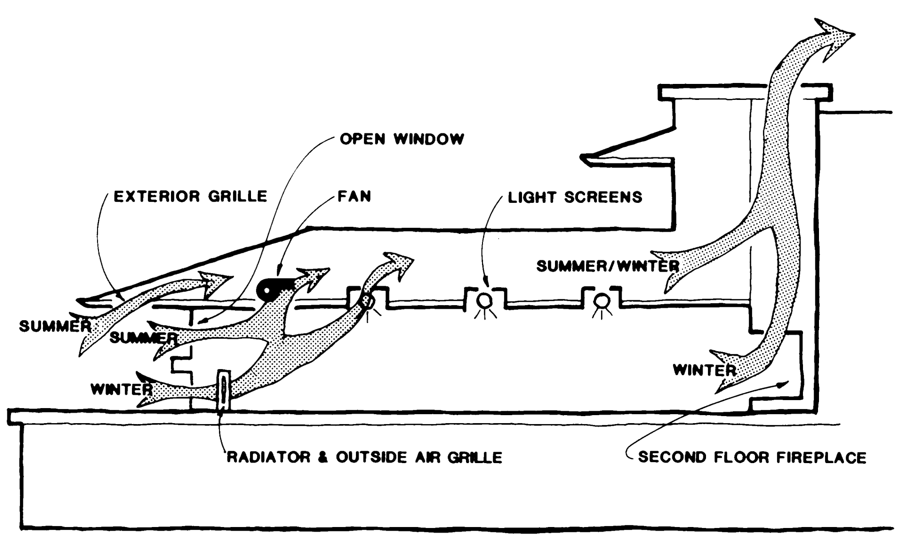
The following features also contribute to the house's summer comfort conditions; but, they cannot be attributed to the uniqueness of Wright's ventilating design because he did not identify occupant comfort as his primary objective or because the features appear in other homes in the area during the same time.

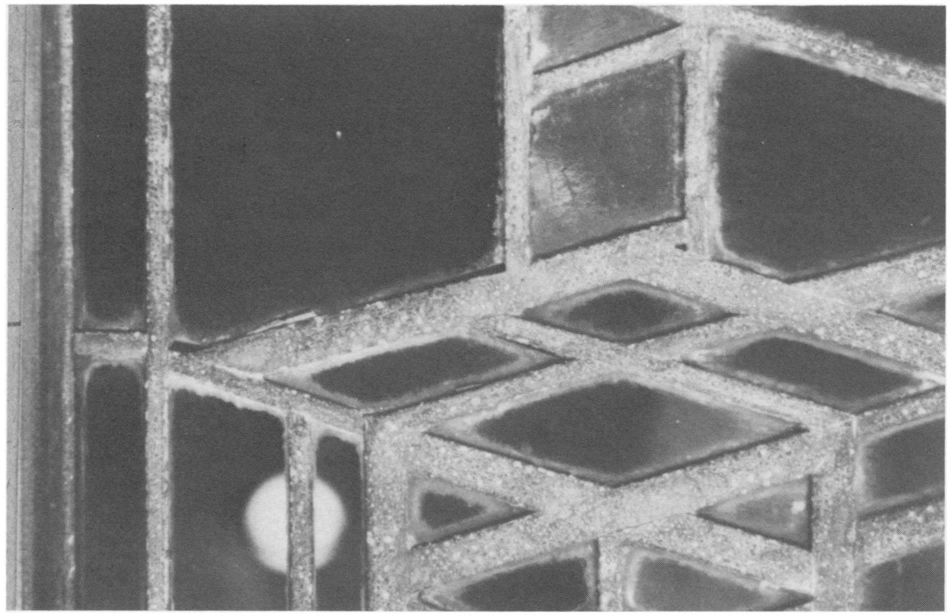
Ceiling plenum ventilation. Wright's aversion to high attic spaces and dormers for ventilation required him to substitute some other means for ventilating the space below the roof. His use of interior ceiling grilles and exterior eave vents allows air to enter, exiting via the ventilator bricks in the chimney. (Joseph Conners[17] disputes Banham's claim that the chimney was expressly designed to accommodate a ventilation function, and only did so incidentally, if at all.)

The practice of ventilating ceiling plenums and the use of ceiling grilles as ventilating devices was not unique, though Wright's integration of lighting, ventilation, and ceiling finish trim in one element is a sensitive design solution to the mundane problem of air circulation. Originally, exhaust fans assisted the ceiling ventilation system. These were as necessary at the turn of the century as they are today, given the convoluted and constricted air-flow passages beneath the low roof. There is no evidence that this system was intended to significantly ventilate the living space; both the architect and this study bear out its negligible effect when compared with the use of the windows and doors.

East-west building orientation. As dictated by conventional solar design, the main axis of the Robie House is east-west, which allows maximum solar exposure in winter while reducing east and west exposure to low sun angles during summer mornings and afternoons. Wright actually designed a solar house in 1936 for Herbert and Katherine Jacobs in which he demonstrated extreme sensitivity to solar angles, thermal mass, earth berming, and prevailing breezes. Nevertheless, it would have been difficult to place a building in any other position on the Robie House site given the site's shape, orientation, views, and available sunlight to the south.

Robie house ventilation is illustrated. The fan, though not original to Wright's design, assists ceiling ventilation.





Oxidation of zinc cames, glass separating from the cames, and accumulating dirt meant windows had to be repaired before they could be made operable.

Ventilation-System Operation

Based on ventilation codes, guidelines in existence at the turn of the century, Frank Lloyd Wright's writings, and observations made at the house by the authors of this study, the original operation of the ventilation system can be described as follows:

Summer

- The primary source of air is the open windows and doors.
- The second floor ceiling plenum is also ventilated. The source of attic air is the exterior grilles under the east and west overhangs, the light screens, as well as mechanical exhaust fans within each end of the living and dining rooms. The hot air then rises through the chimney.

Winter

- The doors and windows are closed. The exterior grilles at the east and west eaves are closed.
- Fresh air enters through the grilles behind perimeter fan-coil units or radiators.
- The air is heated, rises, and is expelled in one of three ways: 1) by exhaust fans at the ends of the living and dining rooms to the ceiling plenum and then out the chimney; 2) through the light screens (No direct evidence was found that the electric lamps were intended to provide heat to induce convection. The small fluorescents in place today definitely will not provide sufficient heat for this purpose.); and 3) through the fireplace.

Security, and Other Issues

The choice of an appropriate cooling strategy for the Robie House depended on considerations beyond modern comfort standards and energy conservation. Some of these issues included security, historic preservation, changed use, and fire protection.

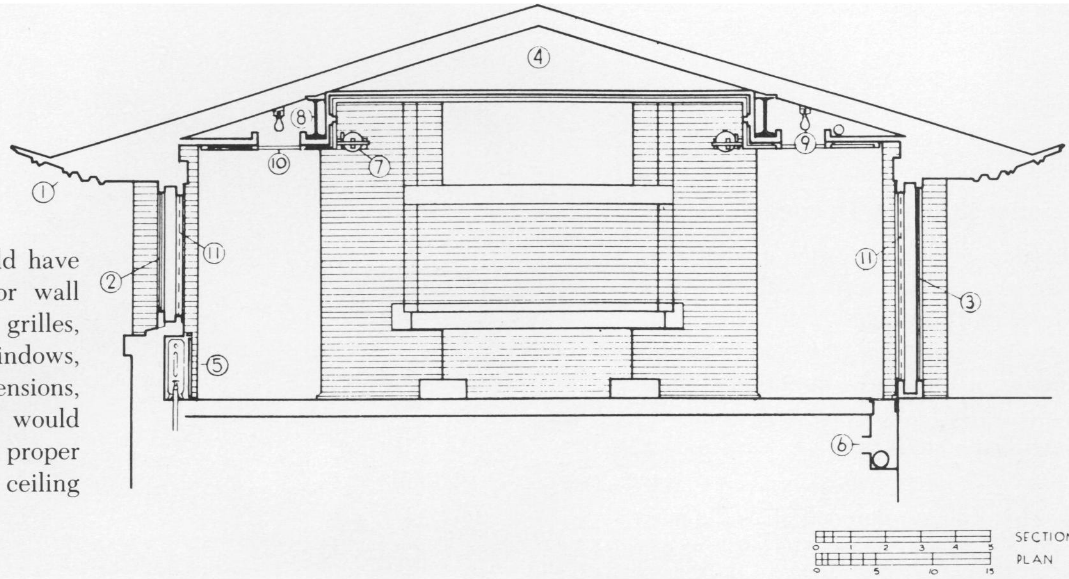
Security was an issue because the doors and windows are primary sources of fresh air, and as such, must be operable. Currently, many of the French doors and north windows on the second floor are nailed shut to prevent their use and forestall further deterioration. This strategy, however, is only a second-rate solution. Nailing woodwork causes additional damage by marring finished surfaces and by creating opportunities for moisture penetration. Furthermore, the glass can still be easily broken and entry gained.

Making the doors and windows fully operable does not have to compromise security. Although Wright did not specify locksets for doors and windows, appropriate fasteners coupled with a standard photoelectric or other security system will improve building security.

Historic preservation of doors and windows was also considered. Use of the doors and windows on a daily basis for natural ventilation would affect their condition. The historic merit of the windows had to be weighed against the degree of proposed use and the condition of the components. Windows in the Robie House were in fairly good condition, but they were fragile. Repeated openings, even for a few large events, could cause enough movement among wooden members to create damaging stress to the panes of glass. This is especially true if guests were allowed to operate the doors and windows themselves.

Mr. John Vinci, AIA, the consulting architect to the University for Robie House renovations, had decided that repairing the doors and windows, and constructing faithful reproductions if necessary, would be acceptable, primarily because the oak members were not particularly unusual in their construction or design. Neither was the hardware special for the time. In 1983, Mr. Vinci recommended that this work receive top priority and estimated costs of $500 per door for reconstructing frames and $945 per door for stabilizing the glazing with new cames, using existing glass where possible. Stabilizing 24 doors would cost $34,680, to which would be added the cost of rebuilding the windows as well. This expenditure, however great, was the most compatible with achieving Wright's original intentions for natural ventilation.

Keeping the doors and windows permanently closed would have been the more compatible strategy if central air conditioning were installed. In this case, the frames and sashes could have been stabilized at much lower cost, while retaining more of the original components. If this option were chosen, provision would have to be made for controlling infiltration. As described in previous sections of this report, this house, like others during the time, was designed to induce flows of fresh air into the living spaces.



"Tightening-up" the house would have required closing off the exterior wall vents, sealing the oak ceiling grilles, weatherstripping all doors and windows, and, to minimize equipment dimensions, some insulation. Condensation would have been controlled through proper detailing of vapor barriers and ceiling plenum ventilation.

Building Use

The question of natural ventilation versus central air conditioning depended heavily on the use of the building. Although there are no immediate plans to change the present occupancy, the restoration committee (composed of interested University staff) had suggested several long-term uses, including: a conference center, a touring center for the university, a tour and architectural center for Hyde Park, a Prairie House museum, a lodging house for distinguished University visitors, and an art gallery.

Some of these uses were more compatible with natural ventilation; for example, lodging house guests would not require air conditioning if most were visiting during the academic year. Use of the building as a gallery or museum, however, would be more compatible with central air conditioning. In this case, large numbers of people and extensive display lights would generate too much heat to dispel by natural means. Furthermore, artifacts on display might require levels of temperature and humidity that could only be provided by central refrigeration. The dimensional stability of woodwork and artifacts within the house would be affected by abrupt changes in temperature and relative humidity. Art conservation concerns also included the issue of atmospheric pollutants such as oxides of sulphur and nitrogen, ozone, and particulate matter (such as dust, soot, and trace materials). These are agents which would accelerate deterioration and increase cleaning and maintenance of not only the historic contents of the building, but also the natural woodwork, plaster, and other finish surfaces. Natural ventilation would not help in this regard. On the other hand, if close climate control were to be achieved by sealing the building and installing central air conditioning, the University had to be prepared to pay the higher cost of energy, especially since night setback might not be recommended because of the climatic stability requirements mentioned above.

Fire Protection. Though not of immediate concern, fire protection and suppression was more compatible with the central air conditioning alternative for two reasons. A sealed interior would have provided greater protection against fire spreading from living areas to vulnerable wood members above. Also, should the University decide to install a fire suppression system later, halon or carbon dioxide systems would probably be favored over water-based systems due to the water damage potential. A sealed building would have been better for containing the released chemicals.

Modern Comfort Standards

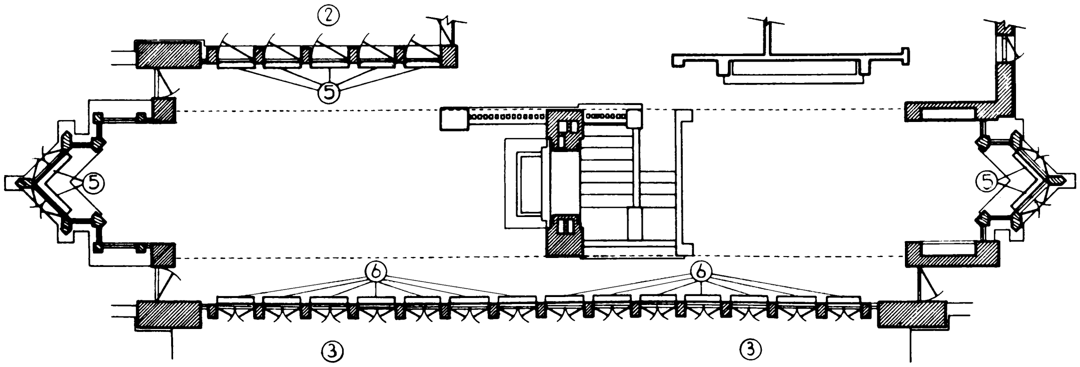
The perception of comfort experienced by human beings is based on the effects of (1) dry bulb temperature, (2) wet bulb temperature, and (3) air movement. A thermal index called Effective Temperature (ET) was originally derived by Houghton and Yaglon in 1923 for the American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). This index combined the effect of dry bulb and wet bulb temperature with air movement to yield an equivalent sensation of warmth or cold.

The original Effective Temperature scale had limitations which were recognized in 1947.[18] The original ET scale over-emphasized the effect of humidity in cooler and in neutral conditions, under-emphasized its effect in warm conditions, and failed to account for air velocity under hot-humid conditions.

Studies in 1961[19] indicated that the temperature criteria for thermal comfort had risen steadily since 1900 from 65°-75°F (18°C-21°C) dry bulb temperature range to 75°-79°F (24°26°C) range. The effective temperature for comfort increased from 65° F (18° C) in 1923 to 68° F (20° C) in 1941. The increasing trend resulted from year-round use of lighter weight clothing and from changing lifestyles, diets, and comfort expectations.

Modern standards of comfort often require mechanical cooling because people's expectations have changed. A few hours of pleasant ambient conditions would allow the mechanical cooling to be shut off, but this is rarely done. Mechanical cooling is used even when there is marginal "free cooling" available in the form of lower ambient temperature and humidity.

The office environment for which the Robie House is being used requires carefully controlled comfort conditions.



First floor section and plan diagrams of lighting, heating, and cooling show the relationship of the three elements: 1) Overhanging eaves control sun; 2-3) Windows and doors provide ventilation; 4) Mechanical extraction draws hot air through ceiling plenum, ducting it to chimney; 5-6) Radiators below windows prevent winter drafts; 7-10) Soffit lights conceal I-beam; 11) Storm sash and screens. (Courtesy, Library of Congress, Mary Reyner Banham, for the Historic American Building Survey)

Analysis of Loads and Natural Cooling Capacities

The primary natural cooling mechanism in Robie House is natural ventilation. In the 80-year period since the house was built, most open areas around the house have been filled with housing and dormitories. Even with the best natural ventilation, the house could only hope to equal outdoor temperature and humidity levels.

In addition to ventilation provided by open windows and doors, Reyner Banham hypothesized that recessed lamps in the meeting rooms were originally supposed to warm air which would then rise and flow under the structural I-beam and out through the attic space and the chimney.[20] Originally, the lamps may have been 40 or 60 watts, compared with the 13-watt lamps currently installed (because the lamps of that time would have given much less light). Thus, the thermal energy which would have provided some air flow is much less now than when the house was designed. Also, the grilles covering the lamps are fitted with a plastic sheet, further inhibiting circulation. No measurable air flow through the 3 electric lamps was found during our investigation.

To investigate the potential for natural cooling, an hour-by-hour computer similation was performed.

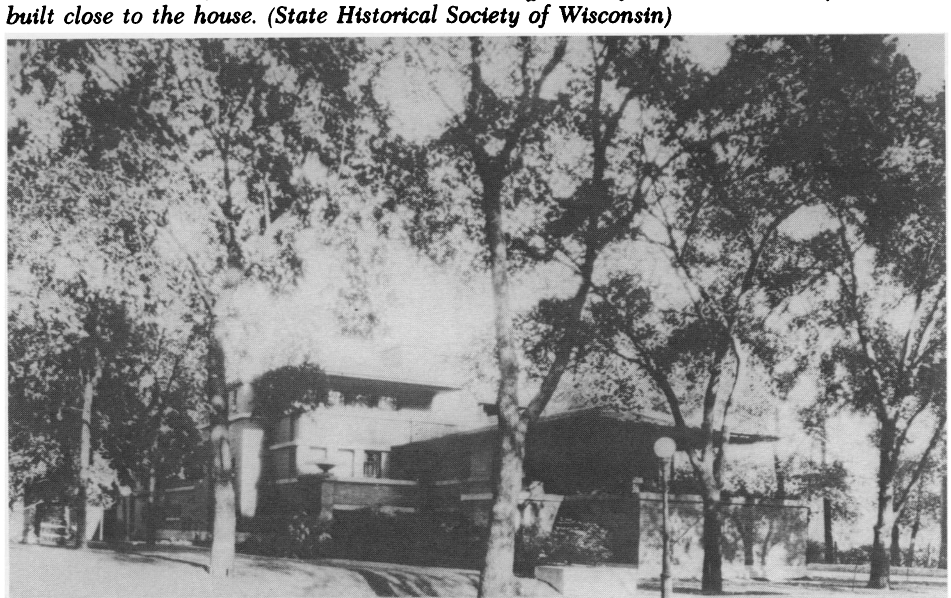
For the yearly simulation, the house was divided into 5 zones: Zone 1, First Floor; Zone 2, Second Floor; Zone 3, Third Floor; Zone 4, Living and Dining Rooms; Zone 5, Kitchen.

The air infiltration rate for Robie House was estimated to be about 3 ACH for all zones. Depending on the number of windows opened in each zone, the natural cooling was simulated by using ventilation which occurred during the occupied hours only. The amount of ventilation used for each zone was estimated from current literature and limited measurements made at the house.

The weather data used for simulation was TMY (Typical Meteorological Year) data from Chicago's O'Hare airport. This site is far from Robie House, but comparable data near Robie House are not available. The summer micro-climate at Robie House is slightly different from O'Hare airport; however, the calculations with TMY weather data represent an optimistic case. The actual natural cooling potential at Robie House would be slightly less.

To simulate natural ventilation, 77° F dry-bulb and 55° F dewpoint temperature were chosen to represent the upper limits of comfort conditions during

When the Robie house was first built, the landscape was open, inviting cooling summer breezes. Since then, the micro-climate has been affected by dormitories and apartments built close to the house. (State Historical Society of Wisconsin)



occupied hours. During the year, there were 684 hours when this condition was exceeded. All these hours were during the summer months.

We developed information to show when individual room temperatures exceeded various dry bulb temperatures. This information was given for all zones. In the third floor zone, for example, the room temperature exceeded 78° F for 379 hours during occupied periods.

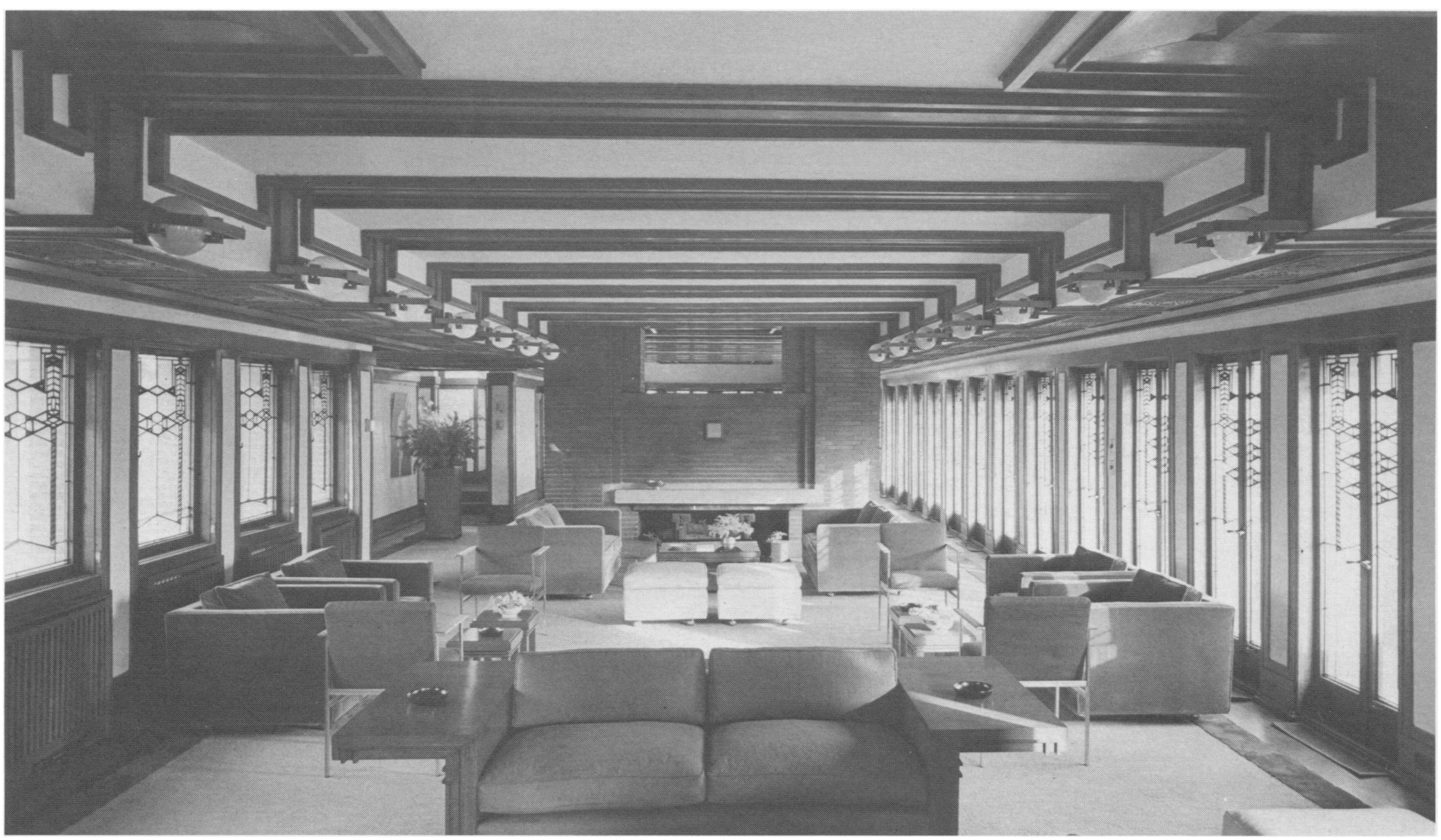
Thus, the natural cooling potential, even if all the windows were opened, was insufficient for occupant comfort. Mechanical cooling was definitely required. To plan for mechanical cooling, the house was divided into five (5) zones. The sporadically occupied zones, such as the living and dining rooms, did not require cooling when not in use.

Examining Options

We recommended that before the University decided on the extent of refrigerated air conditioning, that it consider restoring the garage offices to their original function. The garage is historically significant as one of the first three-car garages and one of the first attached garages in the world. Its design reflects Mr. Robie's interest in experimental motor cars. The original garage design extended the stained glass patterns found in the windows to the gate and the garage door lights. Currently, the garage houses three makeshift offices, cooled with window air conditioners. Restored garages could serve as storage space for the Alumni Affairs offices, thereby freeing up more habitable space inside.

Because the Robie House was designed for natural ventilation, we recommended that natural ventilation be given priority, and that refrigerated cooling be used mainly for peak cooling loads. Refrigerated cooling could be easily installed using the existing two-pipe, fan-coil units and distribution lines which are currently used for heating only. However, existing units would not meet peak loads, and since they are nearly 20 years old, their replacement was imminent. We believed it advisable to install new, larger units which would handle most cooling loads, though not loads from large numbers of people during hot, humid weather. Units capable of handling these extreme loads would be too large to fit in the existing oak cabinets.

Beneath each window on the left is a fan-coil radiator unit, hidden behind a wooden grille. (Richard Nickel, courtesy of Richard Nickel Committee)



Description of Existing System

The entry foyer, billiard room, and playroom on the first floor; living room, dining room, and guest room on the second floor; and all third floor bedrooms are served by a two-pipe, heating only, fan-coil system. The system were installed in the mid 1960's and consisted of vertical and horizontal concealed fan-coil units.

The vertical units were installed in the wooden cabinets at the perimeter walls that originally housed cast-iron radiators. Most of these fan-coil units had been modified to discharge air at the front of the unit in lieu of the standard top discharge; however, no provisions had been made to duct the discharge air from the front of the fan-coil units to the face of the cabinets. It was possible for discharge air to short-circuit in the wooden cabinet.

Four horizontal units were installed in the first floor ceiling cavity and served the living room and dining room on the second floor. Supply air was ducted from these units to four of the original perimeter floor grates at the south side of the second floor. Return air was drawn through the remaining perimeter floor grates at the south side of the second floor and the through the first floor ceiling plenum to the rear of the fan-coil units.

The vertical fan-coil units in the billiard room, at the west end of the living room, and at the east end of the dining room, had provisions for admitting outdoor air for ventilation. The remaining fan-coil units recirculated building air.

All of the fan coils appeared to be in good condition but needed cleaning. The units were also at the end of their expected service life.

Hot water for fan-coil units was supplied from a Weil-McLain gas-fired, cast-iron boiler, Model J-6-B, Series JB. The boiler capacity was 825 MBH input/660 MBH output. Though of uncertain age, the boiler appeared to be in very good condition. The average service life for a boiler of this type is 35 years; however, service lives of 40 to 50 years are common.

Hot water was circulated to the fan-coil units by an ITT Bell & Gossett model PD-39-S in-line booster pump. The age of this pump was also unknown, but it, too, appeared to be in very good condition.

The hot-water circulation system was a mixture of steel and copper pipe. In general, the hot water supply and return piping appeared to be in excellent condition.

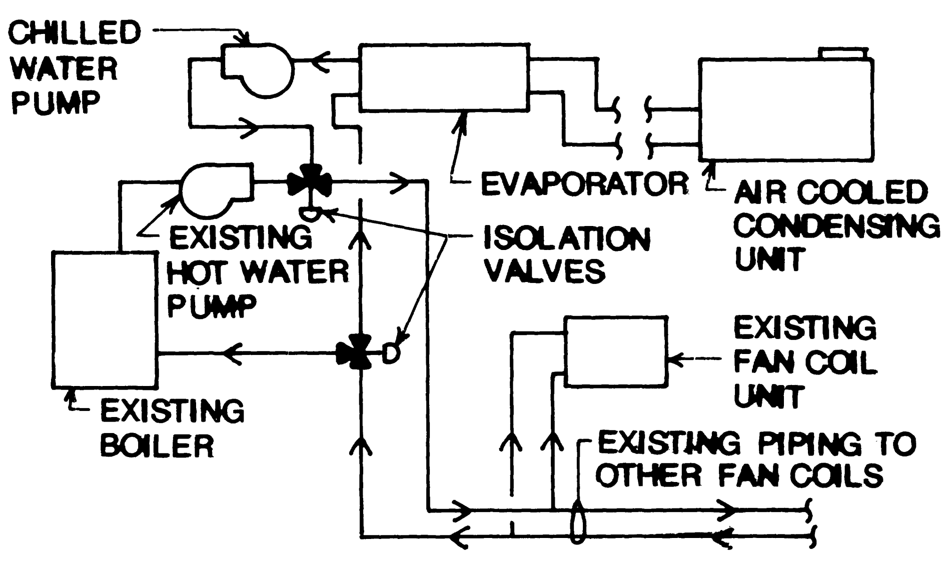
Intent of Modifications

The existing two-pipe fan-coil system could be modified with these additions: 1) a separate air-cooled condensing unit outdoors with a direct expansion/chilled water evaporator, and 2) a chilled water pump indoors to provide chilled water for the fan-coil units during the cooling season.

Little consideration was given to a forced air cooling system because the installation of ductwork and air-handling equipment would have required major alterations to the existing structure. The cost of a forced air system would also be substantially higher because it would not make use of any existing equipment.

The air-cooling condensing unit could be located in the grassy area at the east side of the garage where it would not be readily visible from the street. The unit would be approximately 7 feet long by 6 feet wide by 4 feet high and would require 4 feet of clearance on all four sides. (Size varies depending on unit manufacturer.) Refrigerant suction and liquid lines would be extended from the condensing unit inconspicuously along the outside of the north wall of the building to the boiler room. The refrigerant piping would enter the exterior wall of the boiler room and then extend to the adjacent storage room (formerly the coal bin). The direct-expansion/chilled water evaporator would be suspended from the ceiling of the coal bin at approximately 5 feet above the floor level. The evaporator and pump would be 10 ft. long × 3 ft. wide × 3 ft. high, including piping.

A schematic drawing shows how two-pipe heating and cooling fan-coil system works.



Design Issues

The existing fan-coil units were originally selected for heating, not cooling. To examine the capability of the existing fan-coil units for cooling the Robie House, some assumptions were made regarding its future use and internal cooling loads. The assumptions are as follows:

- The billard room and the playroom will continue to be used as general office space, and the internal loads will remain at approximately their current levels.
- The reception area will continue to be used for its current purpose and internal loads there will be unchanged.
- The living room and dining room will be used for assembly/social purposes (i.e., dinners, receptions, etc.) with a maximum one-hour occupancy of 75 people total in the two rooms. Assuming equal area per person for both rooms, this would allow for 39 people in the living room and 36 people in the dining room.
- The second floor guest bedroom and all of the third floor bedrooms would continue to be used as private offices.
- The lighting levels in all of the rooms would remain unchanged.
- Existing window areas and shading coefficients would remain as they are now, even if the building is renovated.
- Indoor design conditions of 80° F DB/67° F WB (50% RH) would be acceptable for any functions that might take place within the building.
- Chilled water would enter the fan-coil units at 45° F and leave the units at approximately 55° F during full load conditions.
- The building would be opened at 8:00 a.m. in the morning and would not be occupied past 10:00 p.m. in the evening.

Cooling load calculations based on the preceding assumptions indicated that the existing fan-coil units could satisfy the peak cooling loads year-round in the billiard room and playroom but could only satisfy the cooling loads in the remainder of the building for a portion of the year. These two spaces are easier to cool because they are located on the shaded ground floor which is fairly cool.

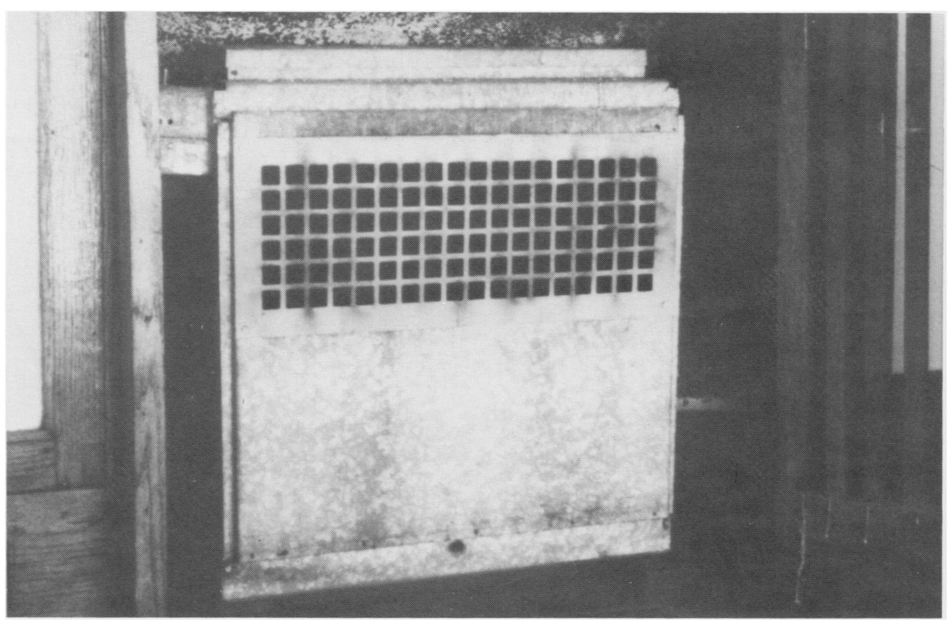
Given the age and the expected service life of the fan-coil units, we suggested consideration be given to replacing the existing units with higher capacity units in the zones where the existing units failed to meet the cooling loads for more than 72 hours per year (2-1/2% of the cooling season). The fan-coils could be replaced with units having greater cooling capacity. However, the replacement units could be no more than two sizes larger than those existing due to the limited amount of space. Also, the existing piping cannot accommodate chilled-water flow rates required for larger units.

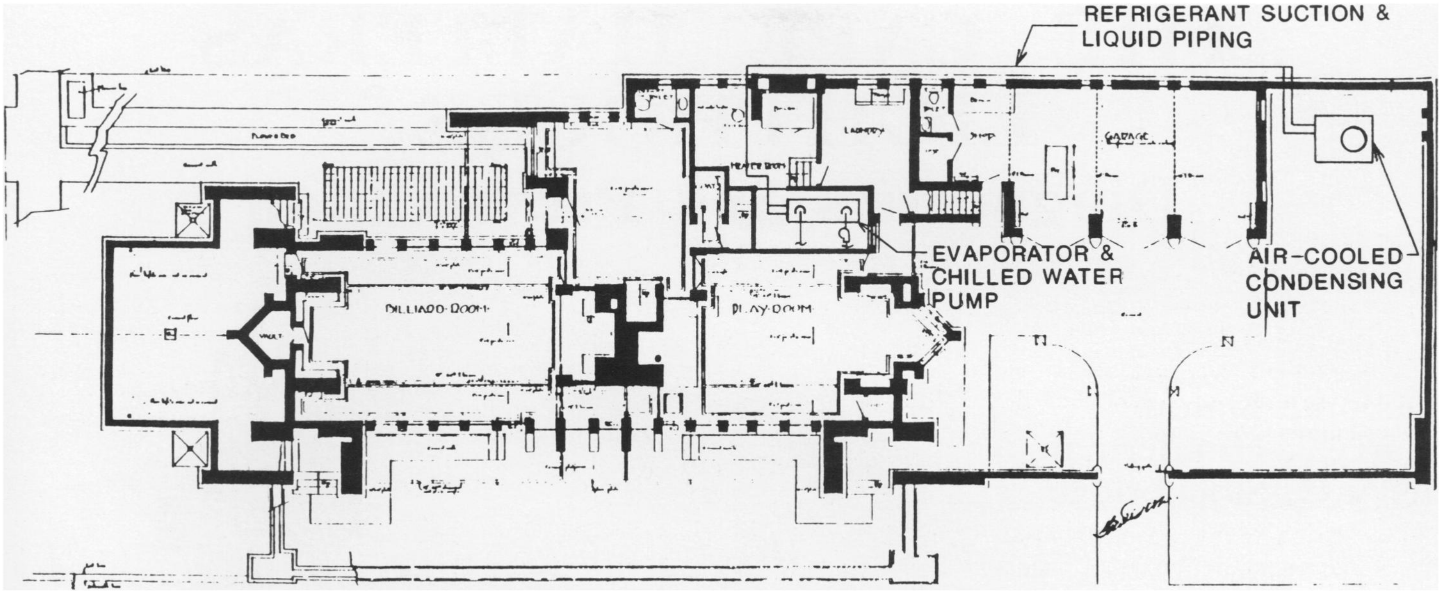
An additional 3 inches of blown-in insulation was recommended as a means of reducing cooling in the third floor bedrooms to reduce the number of hours per year that the third floor bedrooms would be above 85° F DB/67° F WB to 301 hours. Insulation of the roof may not be simple, due to ceiling plenum obstructions and roof construction.

Cleaning and reconditioning of fan-coil units was recommended. Because there is potential for discharge air from vertical concealed units to short circuit inside the cabinets, we recommended that unit discharges be extended to the cabinet exteriors with sheet-metal extensions.

Some units had been installed without condensate drain pans, and none of the discharge piping from the condensate drain pans had been extended to a final drain connection (sanitary sewer or storm drain). This was the major drawback for converting the fan-coil units for use as cooling units. In some areas, ceiling and wall surfaces will have to be disturbed to install condensate drain piping and to extend the piping to a final drain connection. All of the condensate drain piping, existing and new, will have to be insulated.

Larger replacement units can take the place of older fan-coil units. Cabinet size limits the size of replacement units.





Cooling equipment can be sited out of view, near existing boiler.

The existing hot water supply and return piping appeared to be in excellent condition and can be used for chilled water supply and return during the cooling season. The proposed chilled flow rate is approximately equal to the existing hot water flow rate, so the existing pipe sizes should be adequate. The connections to existing piping can be made in the storage room (former coal bin) adjacent to the boiler room and the boiler and existing circulating pump will be isolated so that chilled water will not circulate through them. The garage will also be isolated so that chilled water does not circulate through the cast-iron radiators and fin-tube convection heaters there. The isolation valves for the boiler, hot water circulating pump, and garage will be motorized so that these areas can be placed on-line during the heating season and isolated during the cooling season by operation of a single switch. The same switch will isolate the proposed chilled water evaporator and chilled water circulating pump during the heating season and place them on-line during the cooling season.

Conclusion

Recommendations for cooling had to respect the historic integrity of the Robie House while satisfying comfort needs of its current occupants. The first recommendation suggested that the natural ventilation system be restored. This was also compatible with Wright's preference for natural cooling over refrigerated air conditioning, and would satisfy comfort needs for most of the year. Luckily, Wright's original design, and the existing heating system, could be adapted to modern requirements without a great deal of conflict. Our study demonstrated how modifications could be acceptable to the occupants and to the building's use as a modern office space and conference center.

Notes

1. John S. Billings, A.M., M.D., "Ventilation and Heating," *The Engineering Record* (1893).
2. *Ibid.*
3. Dwight Kimball, *Heating, Piping and Air Conditioning* (June, 1929).
4. Billings, *loc. cit.*
5. Konrad Meier, *Reflections on Heating and Ventilating Engineers*, Annual Address to the New York Branch of the American Society of Mechanical Engineers (1904).
6. *Ibid.*
7. Frank Lloyd Wright, *Modern Architecture* (Princeton, 1931). Reprinted in Edgar Kaufman, *Frank Lloyd Wright: Writings and Buildings* (1960).
8. *Ibid.*
9. Billings, *loc. cit.*
10. *Ibid.*
11. City of Chicago, *Building Inspector's Handbook* (1897).
12. Wasmuth, *Ausgeführte Bauten un Entwürfe* (Berlin, 1910). Reprinted in Frederick Gutheim, ed., *Frank Lloyd Wright on Architecture* (New York, 1941).
13. *Ibid.*
14. *Ibid.*
15. M. Reyner Banham, *The Architecture of the Well-Tempered Environment* (1969).
16. *Ibid.*
17. Joseph Connors, *The Robie House of Frank Lloyd Wright* (1978).
18. C.P. Yaglou, "A Method for Improving Effective Temperature Indices," *ASHVE Transactions* 53 (1947): p. 307.
19. R.G. Nevins, "Psychrometrics and Modern Comfort," presented at the Joint ASHRAE-ASME Meeting (Nov. 28-29, 1961).
20. Banham, *op. cit.*