# HYBRID VENTILATION IN THE HARM A. WEBER ACADEMIC CENTER: A LATE-SUMMER CASE STUDY

Dianne Ahmann[1,2] and Lee Durston[2]

## INTRODUCTION

*Passive ventilation employs a set of strategies, potentially including building shape, internal configuration, orientation, aperture size and position, and microclimate design, to direct air through a building without the assistance of fans or pumps. Passive ventilation has received widespread attention in green building design, particularly in mild climates, because of its great potential to reduce cooling costs. The challenge of predicting airflow speed and direction within a building has encouraged development of sophisticated computational simulation tools, and the resulting confidence has, in turn, led to the design of passive and passive/mechanical hybrid ventilation systems in increasingly extreme climates. The Harm A. Weber Academic Center possesses one of the most ambitious hybrid ventilation systems in the world: in the hot continental climate of the midwestern United States, this building integrates passive and mechanical systems into a single network of airflow pathways. Aperture openings for the system are controlled automatically, using information provided by numerous internal and external sensors, such that the building can make use of multiple hybrid modes to utilize the cooling power of outdoor air to the greatest extent possible. During August 2007, shortly after the peak of the local cooling season, when the building was expected to be under mechanical control, this investigation of the airflow and thermal properties of the new building was undertaken to provide useful information about its early performance.*

## PASSIVE COOLING IN A CHALLENGING CLIMATE

The Weber Center is located near Chicago, IL, with a continental climate of hot, humid summers and cold, windy winters (6459 HDD65°F; 6606 CDH74°F; –4°F winter design dry-bulb; 89/74°F summer design dry bulb/mean coincident wet-bulb (1,2)). The summer mean daily range is 20°F (1), however, which is advantageous for passive cooling strategies: nighttime air may often be cool enough to lower building temperatures substantially. Annual TMY2 data (2) visualized with Climate Consultant 3 software (3) show the extent of the cooling problem in Chicago and much of the continental U.S. (Figure 1a). Many hours of the summer are sufficiently hot and humid that they lie beyond the reach of passive cooling strategies; the important question is, therefore, how passive strategies can best diminish the cooling load in such climates. When data from September–May are considered separately (Figure 1b), it becomes evident that the cooling needs of spring and fall months are highly approachable by passive means, including shading, use of thermal mass to delay daytime cooling loads until cooler evening hours, night ventilation of thermal mass, stack-effect and cross ventilation, and even evaporative cooling (3, 4, 5, 6).

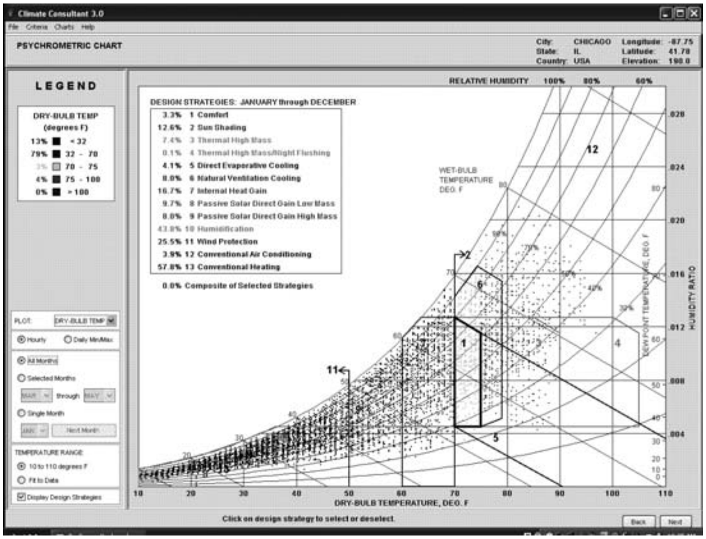
## BUILDING DESIGN

### *Architects and Engineers*

The Weber Center was designed by Alan Short & Associates, a firm known for innovation in passive ventilation (prior work includes the Simonds Farsons Cisk, Malta; Queens Building, DeMontfort University, UK; School of Slavonic & Eastern European Studies, UK; Frederick Lanchester Library, UK; 7, 8, 9). Modeling and simulation of the hybrid ventilation system was conducted by scientists at the Institute of Energy and Sustainable Development at DeMontfort University and the BP Institute for Multiphase Flow at Cambridge University (10, 11). Under the direction of the local architec-

[1]CURRENT ADDRESS: Energy Studies in Buildings Laboratory, University of Oregon, Eugene, OR 97402, dahmann@uoregon.edu.
[2]Building Science Division, BCRA Architecture + Engineering, 2106 Pacific Avenue, Tacoma WA 98402.

a)

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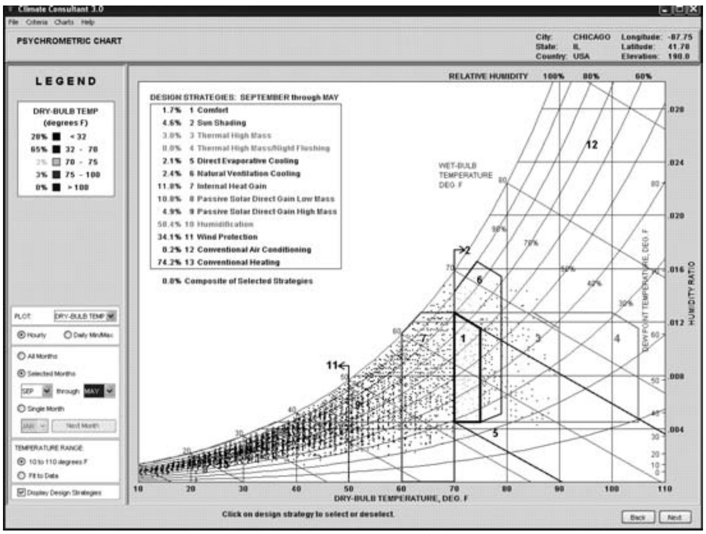


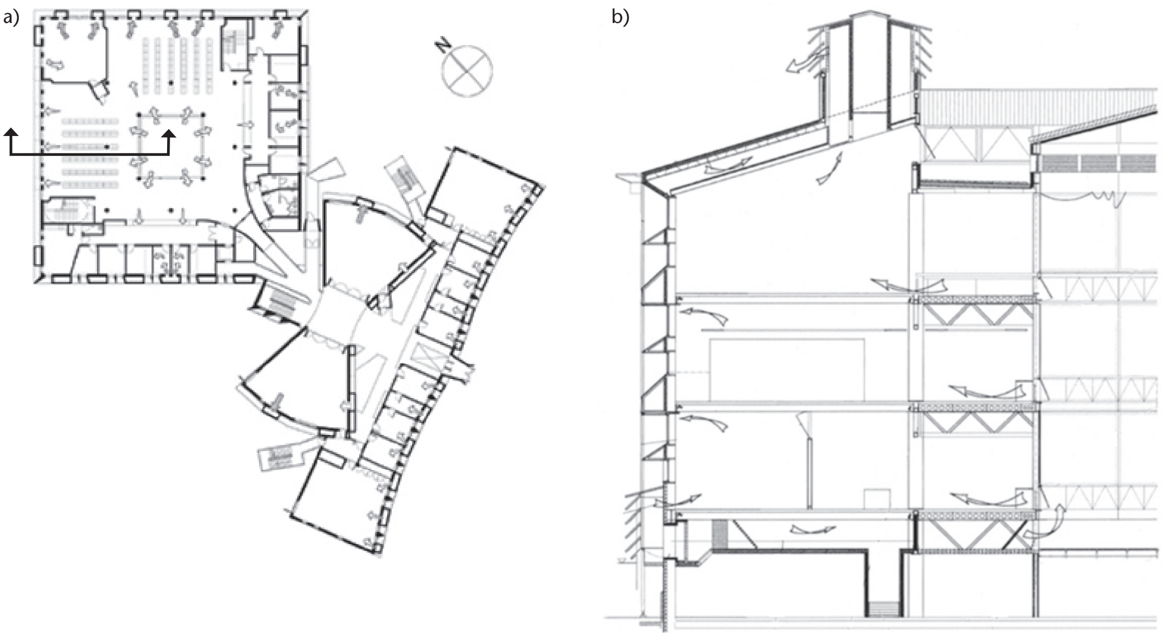

**FIGURE 1. Chicago Climate.** Humidity ratio vs. dry-bulb temperature data (Chicago O'Hare TMY2) for individual hours of the months (a) January–December and (b) September–May (2, 3) show the approachability of spring and fall cooling needs by passive strategies.

ture firm Burnidge Cassell Associates, the building was opened for occupancy on the campus of Judson University, Elgin, IL, in July 2007, with the dedication following in October. The program includes a library, classrooms, design studios, and offices.

### *Spaces*

The building consists of three sections: the "bar," an elongated southern wing where most offices are located; the "block" at the north, containing the library and studios, and the "bowtie," housing classrooms and circulation between the two (Figure 2). All sections contain 4 levels. Within the block, which is the focus of this study, Level 1 holds mechanical facilities and classrooms; Levels 2 and 3 house the library, and Level 4 contains the architecture studios. The large lightwell at the center of the block reaches through Levels 2, 3, and part of 4, and it serves as a central air duct for distribution of both exterior and mechanically-conditioned air. On Level 4, the lightwell is topped by a glass-enclosed space known as the "greenhouse" intended to serve as a thermal buffer between the lightwell and glazed roof (10, 20).

**FIGURE 2.** Drawings of the Weber Center (a) in plan, showing the block, the bowtie, and the bar, from north to south, and (b) in section, showing only the block. Arrows indicate airflow pathways used by both passive and mechanical systems (adapted from 10).




### *Hybrid Ventilation*

Two primary ventilation strategies were employed in the Center, both of which rely on thermal gradients to propel air vertically. "Edge-in, edge-out" ventilation both admits and discharges external air from apertures at the perimeter; this airflow path type was intended for offices in the bar as well as some offices in the block (10). "Center-in, edge-out" ventilation, found only in the block, admits exterior air into a plenum between Levels 1 and 2, conditions it if necessary, and allows it to travel upward through the lightwell. Levels 2, 3, and 4 each have operable glazed louvers at floor level that open automatically to admit lightwell air ("center-in"), which then moves outward and upward through the spaces to be cooled. Air from Levels 1–3 is then released into stacks at the perimeter ("edge-out"), from which it is either directed into one of eight termini on the roof for exhaustion (passive modes) or recirculated to the basement for reconditioning and addition of fresh air (mechanical modes). Level 4 is independently ventilated directly to the outside to avoid backflow of air exhausted from the lower levels (20). Of special significance is the integration of passive and mechanical airflow pathways in the floor plenum, perimeter stacks, and roof plenum, which avoids redundancy of ductwork and controls. In addition, the configuration minimizes fan use by allowing displacement mechanisms to deliver mechanically conditioned as well as outside air to the library and studios (20). Detailed descriptions of the airflow distribution network, operation regimes, and controls have been published by the designers (10, 11, 20).

### *Load Reduction: Thermal Mass and Shading*

Both ventilation strategies were designed to support night ventilation of thermal mass (10, 11), in which building mass is used to minimize air temperature variation by absorbing heat from people, lights, and equipment during the day, when the building is closed to outside air, and then releasing it to cooler air at night when the building is opened (4–6). The Weber Center is, accordingly, a concrete frame building with abundant mass exposed on walls, floors, and ceilings to absorb internal heat. External cooling loads were diminished by use of deeply recessed (shaded) windows, minimizing solar gain, and lighting loads were reduced throughout the building by the central lightwell in addition to abundant clerestory windows on Level 4 (20).

### *Operable Glazing*

Consistent with the goals above, the library was originally designed with fixed rather than operable glazing, thus avoiding cross-ventilation with its accompanying issues of noise, dirt, and security (10, 20). The actual building, however, was found equipped with manually operable windows at view level throughout, with potentially important consequences for building performance.

## HYPOTHESES AND MOTIVATION

The thermal environment of the block portion of the Weber Center was expected to be under primarily mechanical control during August, which is typically the second-greatest cooling month in the American Midwest. Nevertheless, load-reduction lighting and shading strategies were expected to be in effect, and the potential existed for nighttime temperatures to fall low enough for use in nighttime ventilation of thermal mass.

### *Hypotheses*

The field study was therefore guided by the following hypotheses: (1) that the block would have the thermal environment of a conventional building, falling within the thermal comfort zone of ASHRAE Standard 55-2004 (12) as intended by the designers (20), (2) that airflow within the block would follow the intended center-in, edge-out pathway (20): (a) that airflow within the block would be isolated from that of the bowtie, presumably to avoid conflict with the vertical displacement regime, (b) that the lightwell would be operating to deliver conditioned air from Level 1 up to the higher levels, (c) that this air would be discharged through perimeter stacks on Level 3, and through ceiling grilles to the stack termini on Level 4; (3) that a vertical thermal gradient would exist within the building, despite its mechanically-conditioned status, consistent with the use of displacement ventilation to deliver conditioned air; and (4) that solar thermal gain from the greenhouse would be undetectable, presumably due to overhead shading (20). Additional solar gain and daylighting hypotheses concerning perimeter windows were investigated but are not described here.

### *Motivation*

The realization of architectural ideas in built form is a complicated process, and high-performance buildings require detailed commissioning and often years of tuning before reaching their intended efficiencies. Each of these buildings is a valuable experiment with many lessons for future designs; unfortunately, most buildings never receive the investigation that could help successive buildings become increasingly green. The motivation for this study was therefore to learn as much as possible, as early as possible, about a building at the forefront of green design in the United States, both to inform and inspire future design efforts and to assist in tuning of the building itself. This was not a fault-finding mission but an endeavor to support the cause of green design.

## METHODS

### *Date and Duration*

This study was conducted on site at the Harm A. Weber Academic Center (HAWAC) in Elgin, IL from Monday, August 20, 2007 through Friday, August 24, 2007. HAWAC construction was officially completed in April 2007 (13), and occupancy began during the summer (14). At the time of the study, most offices were occupied, library stacks were full, and studio benches were in place. However, classes were not in session, occupancy was correspondingly low, and the presence of construction and engineering crews indicated that finishing work was still in progress. Commissioning was not yet completed, and plant staff were still in operations training (14).

### *Equipment*

The following instruments were generously provided by the Agents of Change Loaner Toolkit program, funded by the U.S. Department of Education, and administered by Professor Alison Kwok through the University of Oregon (15): Onset Hobo U12 Temp/RH/Light/External Dataloggers (accuracy ±0.63°F @ 77°F, ±2.5% RH @ 10–70% RH); Onset Hoboware Software Version 2.0.0; Kestrel 3000 Pocket Weather Meter (accuracy ±3% RH, ±3% airspeed, ±1.8°F; Raytek MT-4 Infrared Thermometer (accuracy ±2%); Testo 405-V2 "Velocity Stick" Hot-Wire

Anemometer (accuracy ±5% airspeed, ±0.9°F); Pilkington Sun Angle Calculator; 40 mm diameter Globe Thermistor (accuracy ±1.3°F @ 68°F); Airflow Indicator Bubbles. Additional equipment was provided by BCRA Architecture + Engineering: FLIR ThermaCAM BX320 Infrared Videocamera; FLIR Quickview 2.0 Software; Hitachi DZ-GX3300 DVD Video Camera; Mannix SAM990DW Weather Station (accuracy ±1.8°F; ±5%RH); Onset H8 Hobo Dataloggers (accuracy ±1.3°F; ±5%RH); Onset TMC6-HD Thermocouples (±0.9°F with H8 dataloggers); and Onset Boxcar Pro Version 4.3.

### *Airflow*

Airspeed and direction were measured repeatedly at specific internal and perimeter locations on Levels 3 and 4 to reveal dominant airflow regimes. Airspeeds were measured by anemometer or, at high velocities, by weather stations as indicated, and airflow directions were determined with flutter-strip apparati built from on-site materials. Infrared photography was used to visualize surface temperatures.

### *Thermal Conditions*

Air temperature and relative humidity were measured at 5-minute intervals with Hobo dataloggers and manually with weather meters. Mean radiant temperatures were approximated with a 40 mm globe thermistor, equilibrated for 10 min, and airspeeds were measured at datalogger locations by anemometer. Data were handled using Microsoft Excel 2003 SP2, and psychrometric charts were produced with the add-in "¡Get Psyched!" (16). Because airspeeds were low (<40fpm) and mean radiant temperatures differed little from air temperatures (<7°F difference), operative temperatures were calculated as the mean of the air and mean radiant temperatures (17) for comparison with the ASHRAE 55-2004 thermal comfort zone. Olgyay-type bioclimatic charts were obtained from *Sun, Wind, & Light: Architectural Design Strategies* (4).

## THERMAL COMFORT

ASHRAE Standard 55-2004 specifies combinations of dry-bulb temperature, thermal radiation, humidity, air speed, activity, and clothing that produce thermal conditions acceptable to a majority of occupants within the space. The temperature component of thermal comfort is therefore described in terms of "operative temperature," the "uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiance plus convection as in the actual nonuniform environment" (12).

The HAWAC, equipped with its multiple hybrid modes of ventilation and a full-size mechanical system (10), was expected to be fully able to cool the block to conventional thermal comfort. Of interest, however, was whether the building would be operated in such a way to realize thermal comfort, given the energy-saving goals of its occupants, and whether any deviations from thermal comfort would reveal useful information about the building's thermal behavior and character.

To record thermal comfort parameters, Hobo dataloggers were deployed at 17 positions throughout Levels 3 and 4 and single positions near the lightwell on Levels 1 and 2, as well as externally (Figure 3). Airspeeds were measured by anemometer, and mean radiant temperatures were estimated by globe thermometer at 8:00 a.m., 12:00 noon, and 4:00 p.m. each day. Examination of these data for three points of interest showed that conditions fell consistently outside the comfort zone, but only slightly so (Figure 4). At 8:00 a.m. on 8/23, outside temperatures were equal to the lowest observed at that hour (see Figure 12 for full thermal data). Level 1 was within the comfort zone, while all locations on Levels 2–4 fell above the zone; some were both too warm and too humid, but some, especially on Levels 2 and 4, were only too humid. External conditions were much more humid than internal positions, but not substantially warmer (Figure 4a). By 12:00 noon on the same day, external conditions became much warmer, but internal conditions remained steady or cooled somewhat, especially on Level 3, while humidities remained above the comfort zone. Level 1 conditions reached the comfort zone boundary, suggesting that the floor plenum air was conditioned only minimally. (Figure 4b). An unusually severe thunderstorm cooled the area dramatically later that afternoon (see Figure 13), causing data from the previous afternoon (4:00 p.m. 8/22) to represent conditions more representatively. At this time, external conditions were the warmest and most humid of the set, yet Levels 1 and 2 became cooler and drier,

**Figure 3.** Positions of Hobo dataloggers projected in section (a) and in plan on Levels 3 (b) and 4 (c).


well within the comfort zone. Conditions on Levels 3 and 4 changed little compared to the noon set, however, suggesting that mechanical cooling had increased, but was not noticeably affecting conditions above Level 2.

An alternative means of viewing thermal comfort, developed by Victor Olgyay (18), shows the effect of airspeed explicitly and therefore enables prediction of airspeeds necessary to provide thermal comfort; this "bioclimatic" visualization is considered especially useful for design and evaluation of passive cooling strategies (4). When dry-bulb temperatures and relative humidities from 8/23, 12:00 noon (for which operative temperature was plotted in Figure 4b) are plotted on a bioclimatic chart (4), it becomes clear that positions on Levels 2, 3, and 4 could have been brought into the bioclimatic comfort zone with slight decreases in relative humidity combined with increases in ambient airspeed: a decrease in dry-bulb temperature would not have been necessary, though it would have served as an effective alternative (Figure 5).

A second alternative, known as the adaptive model of human thermal comfort, is often used to establish comfort criteria in unconditioned buildings and is also incorporated into ASHRAE 55-2004. This approach, which defines the acceptable range of indoor temperatures on the basis of mean monthly outdoor temperatures, was considered by the designers but ultimately discarded in favor of the conventional standard (20).

Hypothesis 1 was therefore proven false: the HAWAC was, in fact, not operated to keep Levels 3 and 4 within the ASHRAE 55-2004 comfort zone during the study. Deviations from the zone were caused by high humidity rather than high temperature, however, and bioclimatic evaluation indicates that airspeeds were also lower than ideal. Consistent with these observations, commentary overheard from occupants referred primarily to air stillness and stuffiness, rather than heat. Increased potential for comfort might therefore be achieved with least energy by approaching humidity and/or airspeed values first, perhaps by making greater use of the lightwell airflow pathway, considered further below, or individually-operable fans.

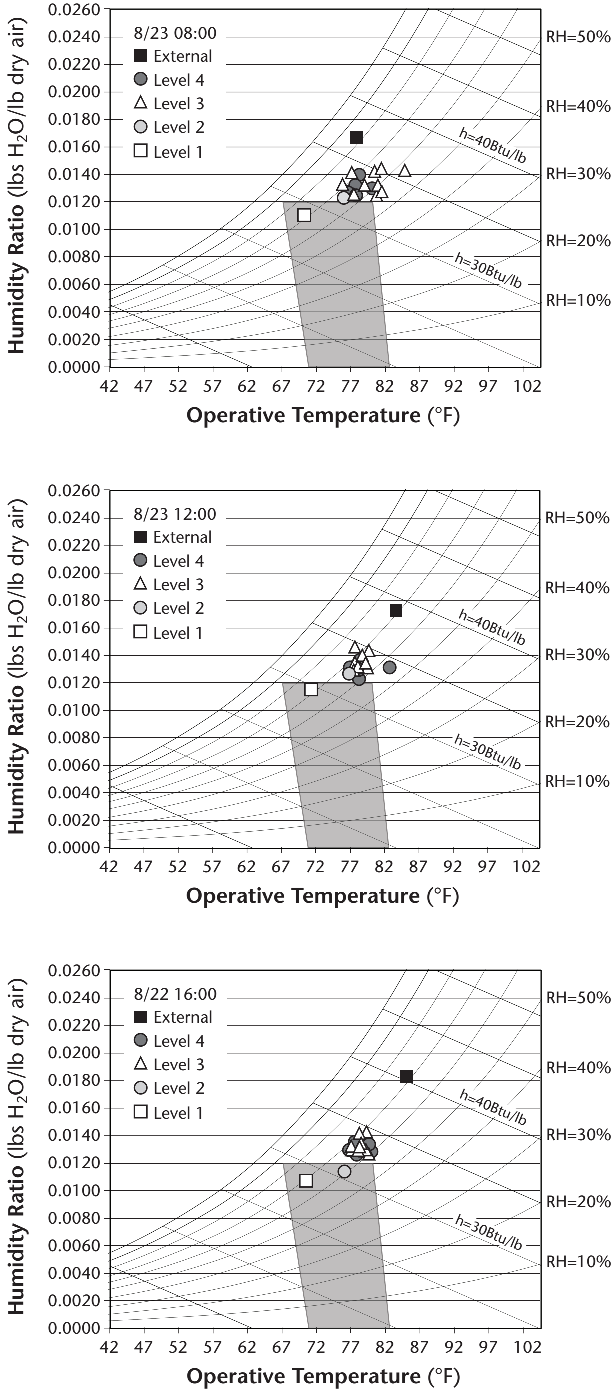
## AIRFLOW ISOLATION WITHIN THE BLOCK

Given the unique emphasis on center-in, edge-out airflow paths within the block, as well as the conditioned, cool, dry status of the bowtie during the study, it was expected that airflow paths within the block would be nearly isolated from the bowtie. At the same time, it was expected that airflow from the lightwell, through the block, to the stack apertures would proceed as described (10, 11, 20). To investigate these hypotheses, all apertures found between Levels 3 and 4, the bowtie, the lightwell, and perimeter stacks were examined with flutter-strip apparati, anemometers, and infrared thermography on multiple occasions each day.

### *Level 3 (Library) Perimeter*

The library on Levels 2 and 3 is served by 23 perimeter stacks embedded within thick walls. Those

**FIGURE 4. Thermal Comfort.** Thermal comfort parameters of (a) 8:00 a.m. 8/23, (b) 12:00 noon 8/23, and (c) 4:00 p.m. 8/22 compared to the ASHRAE 55-2004 thermal comfort zone (shaded) show that internal conditions remained within or near the zone on Levels 1 and 2, while Levels 3 and 4 fell slightly outside the zone due to high humidity rather than temperature, during hot humid weather.



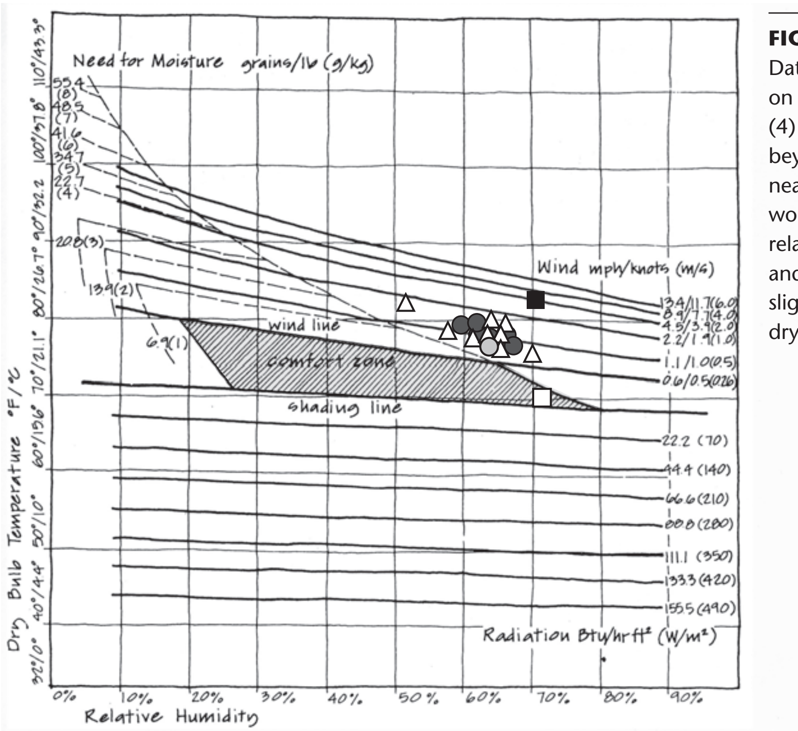



**FIGURE 5. Bioclimatic Chart.** Data from 8/23, 12:00 noon plotted on an Olgyay-type bioclimatic chart (4) show that Levels 2, 3, and 4 lay beyond the comfort zone in the nearly-still air recorded; their positions would have entered the zone if their relative humidities were diminished and ambient airspeeds were increased slightly, as an alternative to diminishing dry-bulb temperatures.

within enclosed rooms were presumably intended to operate with an edge-in, edge-out strategy, leaving 13 exposed to the book stacks. Among these, virtually identical airflow characteristics were found at approx. 9 a.m., 1 p.m., and 4 p.m. on each of 3 consecutive days (8/21–8/23): northeast stack openings, at approx. 10′ height, consistently discharged cool (72–73°F) air into the space, while northwest stacks pulled air outward (Figure 6). Airspeeds measured 10-100+ fpm near the diffusers, but air movement within the book stacks was usually below the detection limit of 2fpm. Consistent with the latter observation, the lightwell louvers at the floor of Level 3 were not observed to open during the study.

Three additional important and unexpected conditions were found during the perimeter investigation of Level 3, all of which occurred near the connection of the block to the bowtie.

At the main entrance (Figure 7a), cool air from the bowtie entered the block at high speed under the double doors (Figure 7b) and through a transfer grille immediately to the east of the entrance that connected to a corridor by restrooms (Figure 7c,d). These two conditions were found consistently throughout the week. In addition, on the west side of the Level 3 entrance, Room 325 was found to open directly to both the bowtie and to the library, connecting the air bodies (Figure 8). Doors were found propped open throughout the study period, allowing airflows between 200 and 300fpm to be observed consistently. At the time of the photographs, the inflowing air was several degrees cooler (73°F) than the ambient library air (76°F).

Overall, therefore, Level 3 airflow patterns were dominated by high-speed entry of conditioned air from the bowtie into the library at the southeast corner. Secondary airflow patterns were characterized by delivery of cool air along the northeast side and uptake of ambient air along the northwest side (Figure 6). Except for these areas, ambient airspeed was quite low (0–5fpm). Mechanical engineers interviewed on-site were surprised to learn that Level 3 was such a strong low-pressure zone in the building, describing the design intent as one in which the block supplied air to the bowtie (19). Not only was Level 3 failing to provide such air, but its apparent

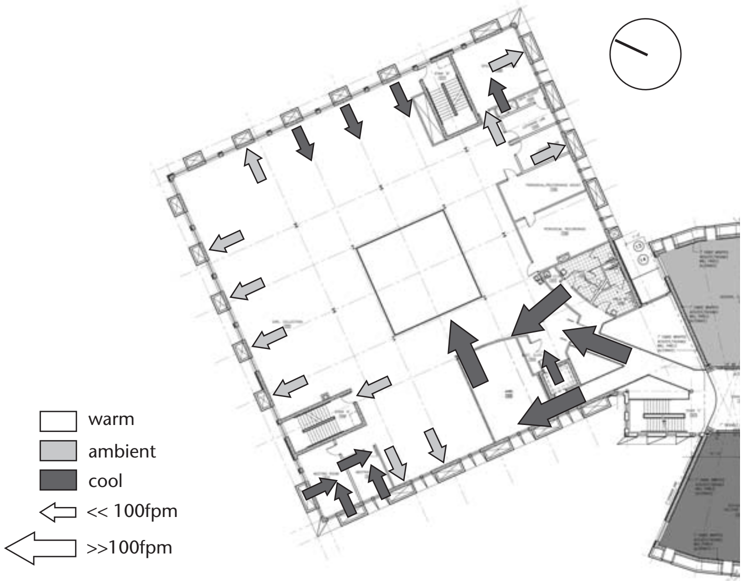



**FIGURE 6. Level 3 Airflow Summary.** Airflow pathways showing predominant speed, direction, and temperature (≥ 5 of 9 occasions) are shown; note in particular the influx of cool air from the bowtie at the southeast entrance to the library (detailed in Figures 7 and 8).

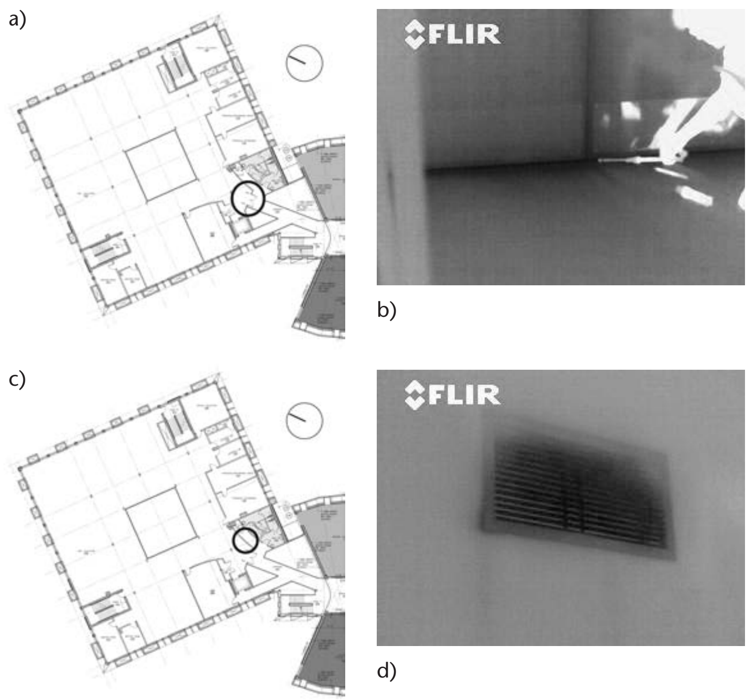



**FIGURE 7. Library Entrance.** At the Level 3 entrance to the library (a), infrared thermography showed the influx of cool (73°F) air from the bowtie under the 78°F entry door to the library (b). Similar influx occurred through a transfer grille to the east of the entry (c), also shown thermographically (d). Airspeed mode: 340fpm; maximum: >370fpm. Measurements at the two openings differed by <10%.

stillness may have been the factor that encouraged occupants to prop doors open, breaching the threshold between block and bowtie ventilation regimes and unintentionally increasing the whole-building cooling load by draining conditioned air from the bowtie.

### *Level 4 (Studio)*

Level 4 is ventilated independently of Levels 1–3 by means of ceiling grilles high on the vaulted ceiling, just below the lightwell openings (Figure 3a), at 4 locations (20). Level 4 possesses a double-door entrance to the bowtie like that of Level 3, in addition

**FIGURE 8. Office Short Circuit: Room 325.** The position of Room 325 (a) enabled bowtie air to pass freely from the south door (b) into the library through the north door (c), as visualized in the library with bubbles blown from inside the office (d). Airspeed mode: 210fpm; airspeed maximum: >300fpm.

a) b) c)


d)

to two stairwell openings, two seminar rooms with thermostats and mechanical air conditioning grilles, and an unsealed glass door opening to the greenhouse at the top of the lightwell (Figure 3b).

Consistent with observations on Level 3, cool (≤72°F) air from the bowtie entered Level 4 of the block at high speed from the south double-door entrance and from the west stairwell (Figure 9). Air of ambient temperature entered Level 4 at similar velocity from the east stairwell, presumably originating from lower levels of the block rather than the bowtie. Mechanically-conditioned air (≤65°F) was provided consistently through grilles in seminar rooms 425 and 433; these thermostats were found set at 76°F. Cool air also entered the studios at high speed from the lightwell louvers, below the platform, on two afternoons. Airflows into the ceiling grilles, however, were below detection limit on all eight occasions measured (Figure 9).

Two important airflow anomalies were also discovered on Level 4, both involving sizable influxes of warm air from the building exterior. On the east side of the studios (Figure 10a), a single operable window was found partly open on 8/21 and remained open for the duration of the study. Measurements showed high-speed entry of warmer-than-ambient air; thermal characteristics were recorded by infrared photography and airflow patterns, as revealed by bubble motion, were recorded by videocamera (Figure 10b).

The glass door to the greenhouse (Figure 11a, b) was similarly found to admit abundant warm air to the studios (Figure 11c). This door was unsealed and opened directly from the platform onto the thermal buffer between the glazed lightwell roof and the ventilatory chamber of the lightwell. While the greenhouse was both shaded (Figure 13) and ventilated by clerestory windows, the internal temperature nevertheless reached nearly 90°F during late afternoons, and warm air was found flowing into the platform space consistently throughout the week.

With all inputs considered, Level 4 appeared to be an even stronger low-pressure zone than Level 3, despite the consistent provision of (conditioned) air to the seminar rooms, 425 and 433. Cool air entered

**FIGURE 9. Level 4 Airflow Summary.** Airflow pathways showing predominant speed, direction, and temperature (≥ 5 of 9 occasions) are shown; note the strong influx of warm air from an open NW window and from the greenhouse, as well as the influx of cool air from the bowtie.

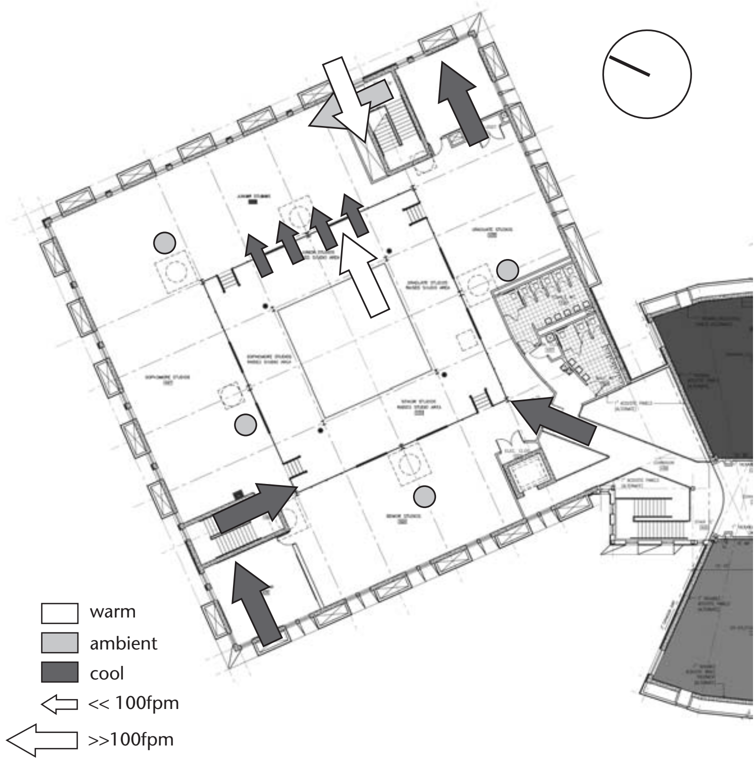
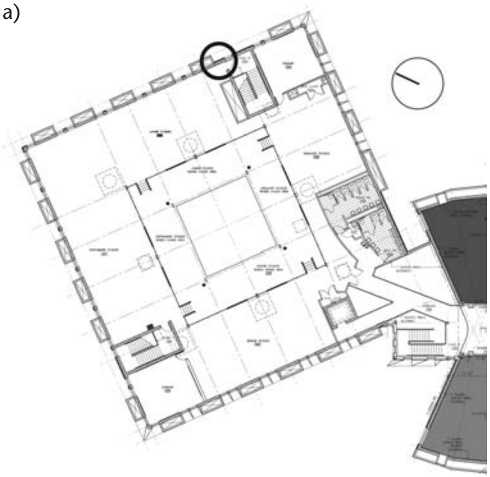



**FIGURE 10. Open Studio Window.** An open window on the NW side of the Level 4 studios (a) allowed warm humid air to flow into the space, as shown by motion of bubbles near the window (b). Airspeed mode: 150fpm; maximum: 310fpm; entry air temperature: 76°F; ambient air temperature: 72.5°F. (8/21/07; 10:42 a.m.).

a)



b)

**FIGURE 11. Greenhouse Door.** The greenhouse on Level 4 possessed an unsealed glass door on the northwest side (a, b), allowing warm air to enter, as viewed against the adjacent soffit (b, c). Airspeed mode: 140fpm; maximum: >400fpm; entry air temperature: 87.2°F; ambient air temperature: 74.5°F. (8/21/07, 11:36 a.m.).


a) b) c)

at high speed from the west stairwell and south double-door entrance, as well as from the lightwell on the two occasions when its vents opened under the platform, while warm humid outside air entered similarly rapidly through an open perimeter window and the unsealed greenhouse door. Level 4 air must have been discharged from some location, among which the ceiling grilles appeared most likely, but airspeeds near these grilles and all other potential discharge locations were below the detection limit of the instruments (~2fpm) and the bubbles, with the result that a discharge pathway could not be confirmed. Of interest was the discovery on 8/24 that the louvers in the stack termini were closed and had not yet been electrically connected, implying that the stack termini could not have discharged air above the roof during the study, and therefore that air reaching the roof plenum must have been recirculated to the mechanical room in the basement.

The similar low-pressure behaviors of Levels 3 and 4, despite the presence of numerous intended and unintended air supplies, combined with an ambient stillness in most occupied areas, showed that still greater air supply to these levels will be necessary to reverse the relationship of the block and the bowtie and to improve thermal comfort by increasing ambient airspeeds.

Hypothesis 2a, that airflows within the block would be isolated from those of the bowtie, was therefore shown to be false: the airflow regime of the block appeared instead to be highly connected to that of the bowtie, and indeed the connections were by far the strongest airflow pathways found, with potential to dominate intended ventilation pathways. Hypothesis 2b, that the lightwell would be operating to deliver conditioned air up to Levels 2–4, was supported in that louvers opened to Level 4 on at least two occasions; however, the louvers to Levels 2 and 3 were not observed to open at any time, in contrast to expectation. The apparently minimal use of the lightwell as an air duct was a surprising finding of the study. Hypothesis 2c, that the center-in, edge-out pathway would be completed by discharge of air to perimeter stacks, was found to be true in regions of Level 3, particularly along the western edges, but the analogous situation on Level 4 (discharge through ceiling grilles) could not be detected.

We consulted with Professor Kevin Lomas with respect to these observations, and he replied that "observed internal pressures, airflow directions, and resulting zone temperatures could have been a consequence of the HVAC system and controls failing to operate as intended. In particular, the lack of air supply through the (closed) air inlets around the lightwell at Levels 3 and 4 could explain many of the observations, and could have been caused simply by incorrect control settings, component failure, or, perhaps, a deliberate overriding of the planned operating mode" (21). Further investigation of the mechanical system operation and resulting airflows between the block and its surroundings (the bowtie, the greenhouse, and the exterior) is therefore essential to discover the source(s) of these problems.

## THERMAL STRATIFICATION

Because of the configuration of the airflow pathways, including the use of the same pathways for both passive and active airflow, we expected to find a vertical thermal gradient within the block even if it were predominantly under mechanical cooling. To characterize the vertical thermal character of the block, Hobo dataloggers were deployed in a vertical column along the southeast side of the lightwell (Figure 12a), as well as outside for reference, to measure dry-bulb temperature, humidity, and light (Figure 12b). Each datalogger was placed out of reach of direct sunlight.

Results showed that a vertical gradient of several degrees did indeed exist within the building throughout the week. Level 1 was coolest, consistent with its lowest position, its proximity to the conditioned air source, and its direct connection to the bowtie through propped-open double doors. In addition, several panels were missing in the Level 1 ceiling, providing a direct connection to the conditioned air plenum that may not have been intended.

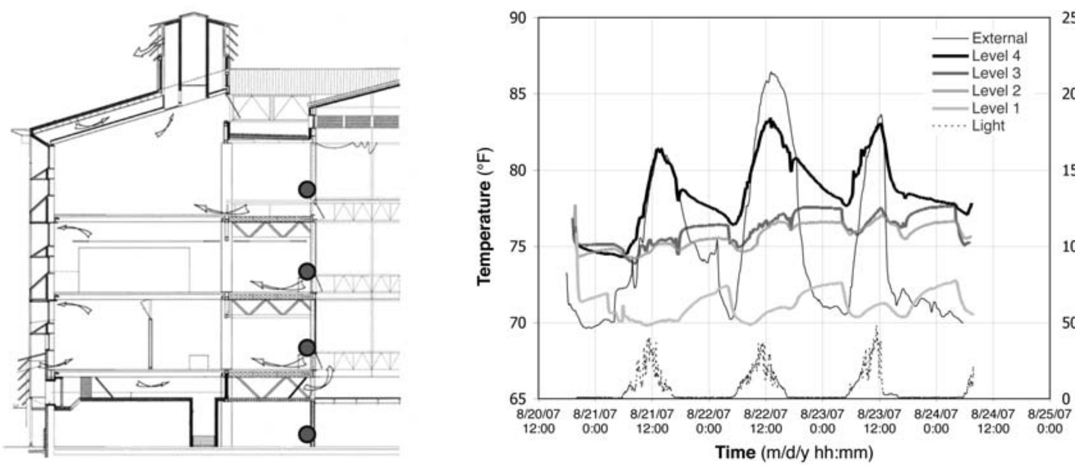
Levels 2 and 3 were several degrees warmer than Level 1 but quite similar to each other, ranging from 74°F to 77°F, with Level 3 slightly warmer than Level 2. On each of the three lower levels, temperatures were lowest in the late morning and highest at nighttime, showing the effect of tighter mechanical control during occupied hours. Level 4 near the lightwell, however, showed a markedly different profile: temperatures rose and fell in close correspondence to outside temperatures, reaching >80°F each afternoon and dropping below 75°F on only one night. Numerous factors apparently contributed to the warmth at this position, including warm air input through the open northeast window and the unsealed greenhouse door described above. Radiant input from the greenhouse was another potential contributor, described below.

Hypothesis 3 was therefore confirmed: during the study, vertical thermal stratification was present consistently within the block. However, the anticipated mechanism for this stratification, namely the delivery of conditioned air in such a way that slightly warmer air was provided to the higher levels, did not appear to explain the observation because the lightwell appeared fully closed to Levels 2 and 3 and only briefly open to Level 4.

## SOLAR GAIN FROM THE LIGHTWELL

The lightwell is the centerpiece of the daylighting strategy in the HAWAC as well as the hybrid ventilation strategy, and its size and extent admit abundant light even to Level 1. Toplight carries the potential for excessive heat gain, however, leading us to investigate the impact of the lightwell on the thermal environment of the block.

**FIGURE 12. Thermal Stratification.** Dry-bulb temperature and light were measured at the work plane on each level (a) and outside for reference by Hobo dataloggers; data are shown at 5-minute intervals (b).




a) b)

In possible anticipation of heat gain issues, the greenhouse was designed as a thermal barrier between the exterior environment and the top of the lightwell (10); it therefore possesses a glass floor at the height of the Level 4 platform. The greenhouse also has clerestory louvers around its perimeter that opened each afternoon of the study, presumably to mitigate overheating of the internal air, as well as internal retractable shade cloths (Figure 13). The latter were fully deployed or deployed on all but the NW quadrant throughout the study.

As indicated above (Figure 11), the greenhouse contributed warm air to Level 4 through an unsealed glass door. It appeared to contribute radiant heat as well, however, as evidenced by infrared photography (Figure 14), potentially affecting not only the dry bulb temperature but also the mean radiant temperature of the space.

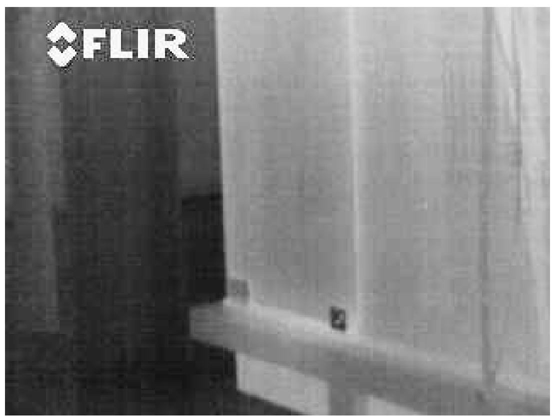
Thermal impacts of the lightwell were assessed by examining temperature and relative humidity patterns in transects across Levels 3 and 4 (Figures 15b, 16b??), in light of the observation that mechanically conditioned air of the bowtie was not only cooler but also substantially drier than outside air. Separate experiments showed that perimeter windows did not contribute detectably to internal heat gain, to the great credit of the perimeter shading strategy (data not shown).

From the lightwell outward to the seminar rooms, temperatures dropped noticeably (Figure 15b). This radial thermal gradient was expected, because the seminar rooms were conditioned, even if modestly. The similarity in temperatures of the E and W platform corners was not expected, however, given the minimal conditioning of the studio space and the exposure of the E platform corner to considerable outside air via the NE open window described above. Relative humidity measurements among the three central positions confirmed that the E platform corner experienced a noticeably greater proportion of humid outside air than the others (Figure 15c). Given its air supply, its temperature was also expected to be greater than that of the W platform corner. The fact that it was not emphasized the thermal role of the greenhouse in warming the studio spaces during the study.

Near the lightwell on Level 3 (Figure 16a), temperatures varied strongly by position. The north

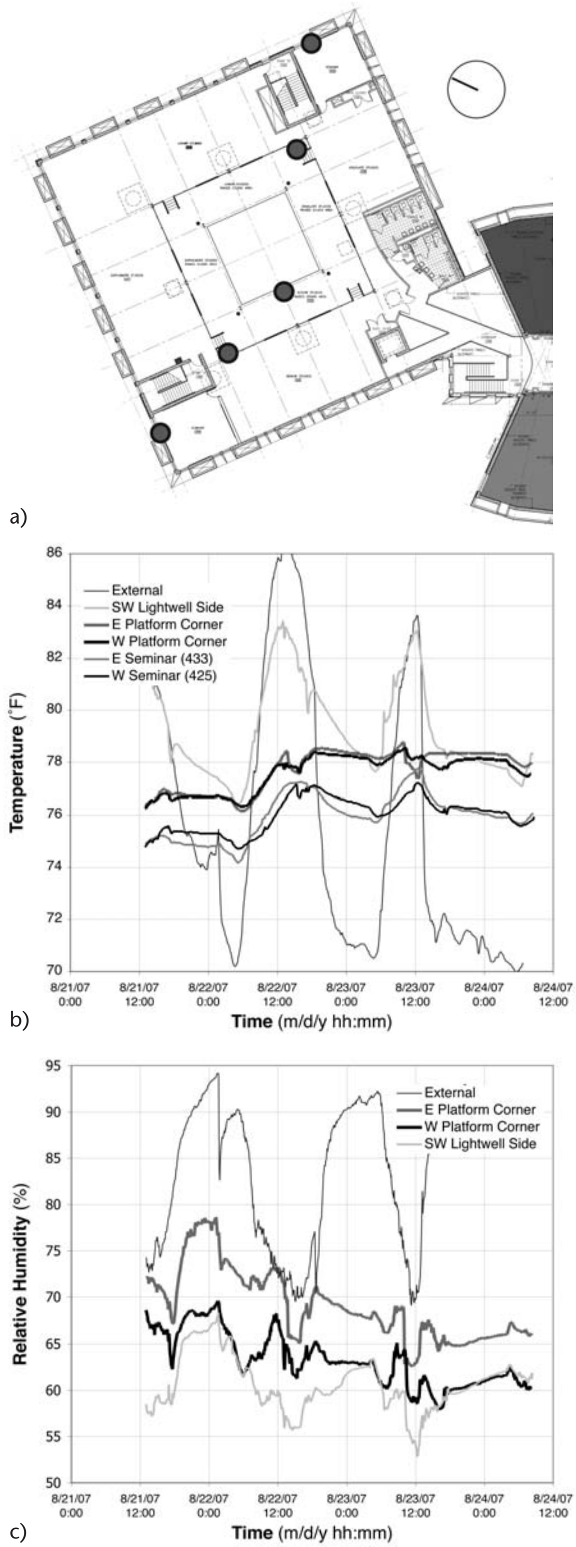
**FIGURE 13. Greenhouse Shading.** The greenhouse, at the top of the lightwell, was equipped with retractable shade cloths that were deployed on all, or all but the NW quadrant, throughout the study.

**FIGURE 14. Greenhouse Radiance.** Infrared photography shows the warmth of greenhouse glass as viewed from the Level 4 platform; warmer temperatures are lighter in color.




corner of the lightwell was consistently warmest, followed by  the east, with the southwest coolest. This pattern could have been created by cooling of the SW position and, to a lesser extent, the E position, by cool air from the bowtie and from the office short circuit, documented above. In addition, sufficient solar energy could have passed through the greenhouse shades, primarily from the south, to enter and warm the north side of the library (Figure 17).

**FIGURE 15. Lightwell Heat Gain: Level 4.** Hobo dataloggers were deployed at the working plane in an E-W transect across Level 4 (a). Dry-bulb temperatures (b) showed diminishing warmth with distance from the greenhouse, while relative humidities (c) showed the contribution of humid outside air from the open window to the east platform corner.



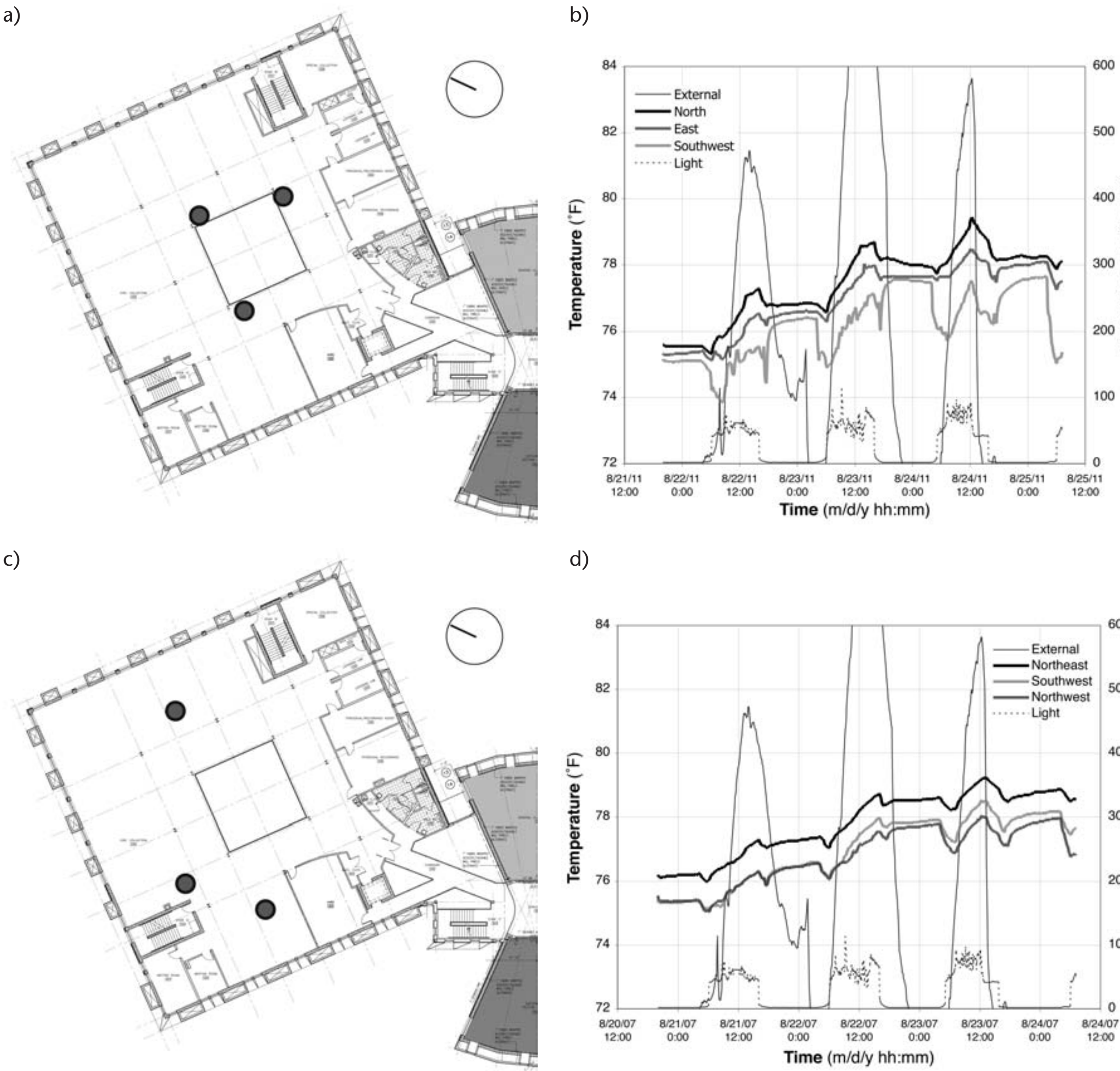

While the former explanation would have been consistent with lower relative humidity readings on the SW and SE sides, relative humidities were found in fact to be higher at these positions (Figure 18). A likely explanation for this finding is that the drier NE side was the recipient of conditioned air from the perimeter stacks (Figure 6), which appeared to dominate the humidity signature of the northernmost locations. The northern regions of Level 3 were therefore both the warmest and the most conditioned (driest), a phenomenon that could only have occurred with the input of local heat from the lightwell. Hypothesis 4, that solar gain from the lightwell would be undetectable, was therefore shown to be false: indeed, heat from the lightwell was found to be a strong influence on temperatures on both Levels 3 and 4.

## CONCLUSIONS AND RECOMMENDATIONS

### *Thermal Comfort*

Subjectively, we found the block environment to be warm and humid during most working hours. Discomfort was mild, however, and the block was much more comfortable than the exterior; nevertheless, opening of the lightwell to Level 4 on two afternoons brought welcome cooling, as did entry to the bowtie or descent into Level 1. Occupants, wearing <0.5 Clo and engaged in 1–2 Mets of activity, were overheard describing the air on occasion as “stuffy,” “sticky,” and “clammy.” Numerous measurements showing warm temperatures and moderately high humidities, combined with low air movement, bore out these perceptions in comparison with both standard and bioclimatic assessments of thermal comfort. The most important changes that could be made are (1) to increase airspeed to 10–30 fpm and (2) to dehumidify, especially by passive or low-energy means. Lowering dry-bulb temperatures, ide-

**FIGURE 16.** Lightwell Heat Gain: Level 3. Dataloggers around the lightwell of Level 3 showed thermal asymmetries of several degrees (b), with the north side warmest, a pattern that was visible in the stacks (c) as well (d).




ally by external shading of the lightwell, would also improve conditions; lowering dry-bulb temperatures actively is a lower priority.

### *Airflow Patterns*

The block was a strong low-pressure zone during the study, and airflows on Levels 3 and 4 were dominated by high-speed entry of conditioned air from the bowtie as well as warm humid air from the perimeter and the greenhouse. This situation was opposite to the design intent stated by the mechanical engineers on-site (19), though not published by the designers, in which the block was to supply air to the bowtie, and caused the block to be unexpectedly vulnerable to outside conditions. Tight control over manually-operable perimeter and greenhouse apertures will clearly be essential during the most extreme part of the cooling season and will undoubtedly be implemented before the summer of 2008; in addition, connections at the block-bowtie interface

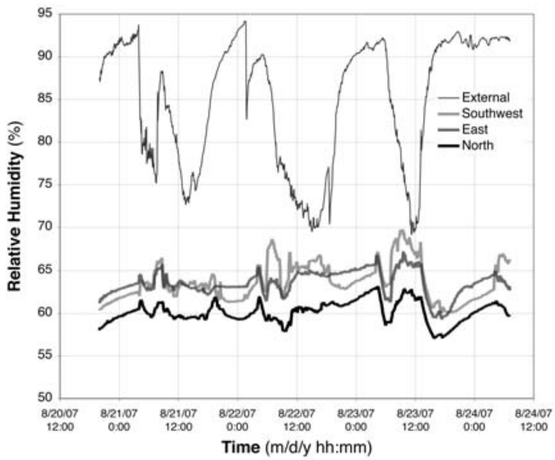
**FIGURE 17. Lightwell Direct Sunlight.** Direct sunlight from the lightwell is shown illuminating the north glazed surfaces of the lightwell; Levels 3 and 2 of the library are visible beyond.

may need secondary double-doors to uncouple the two spaces, and airflow outward from the block will need to be increased substantially to support this effort in fulfillment of the design intent. While the center-in, edge-out airflow pathway was not observed on Level 3, the lightwell did deliver abundant cool air to Level 4 on two afternoons, fulfilling the "center-in" component. The "edge-out" component was not detectable, unfortunately. Further experimentation and observation will be of great use to reveal the sensitivity of airflow pathways to lightwell openness, perimeter stack openness, connectivity at the bowtie, and thermal conditions in the lightwell.

### *Thermal Stratification*

Occupied spaces in the block were found to be thermally stratified, with Level 1 substantially cooler and Level 4 substantially warmer than Levels 2

**FIGURE 18. Relative Humidity: Level 3.** While the cooler south-side temperatures could have been attributed to the influence of bowtie air, these positions were actually more humid than the north side, suggesting that the north was receiving more conditioned air overall (see Figure 6) and implicating lightwell heat gain in the warmer north side temperatures.




and 3. While this was expected as a consequence of displacement delivery of conditioned air through the lightwell, it was not expected that the lightwell would appear as an important contributor to local warmth.

### *Lightwell Solar Heat Gain*

The greenhouse and lightwell were important thermal contributors on Levels 3 and 4, as shown by the persistence of greenhouse- and lightwell-induced thermal gradients despite counteracting influences of mechanical conditioning and unintended airflows through windows, offices, and stairwells. On Level 3, the dominant pattern was a north-to-south gradient, with the north side warmest, both because it was able to receive southern sunlight through the lightwell glazing, and because cool air was entering the south corner from the bowtie. On Level 4, the dominant pattern was a radial thermal gradient, warmest at the center. While interior shadecloths were drawn across the greenhouse roof, these were apparently insufficient, and external shading for the greenhouse should be a top priority in future work.

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