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The Integration of Engineering and Architecture:
A Perspective on Natural Ventilation for the New San Francisco
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Abstract

A description of the in-progress design of a new Federal Office Building for San Francisco is used to illustrate a number of issues arising in the design of large, naturally ventilated office buildings. These issues include the need for an integrated approach to design involving the architects, mechanical and structural engineers, lighting designers and specialist simulation modelers. In particular, the use of natural ventilation, and the avoidance of air-conditioning, depends on the high degree of exposed thermal mass made possible by the structural scheme and by the minimization of solar heat gains while maintaining the good daylighting that results from optimization of the façade. Another issue was the need for a radical change in interior space planning in order to enhance the natural ventilation; all the individual enclosed offices are located along the central spine of each floorplate rather than at the perimeter. The role of integration in deterring the undermining of the design through value engineering is discussed. The comfort criteria for the building were established based on the recent extension to the ASHRAE comfort standard based on the adaptive model for naturally ventilated buildings. The building energy simulation program EnergyPlus was used to compare the performance of different natural ventilation strategies. The results indicate that, in the San Francisco climate, wind-driven ventilation provides sufficient nocturnal cooling to maintain comfortable conditions and that external chimneys do not provide significant additional ventilation at times when it would be beneficial.

Introduction

In 1998, the commission for a new federal office building in San Francisco was awarded based on the result of a competitive design process managed by the Design Excellence Program of the General Services Administration (G.S.A.). Among other goals, the program seeks to “produce facilities that reflect the dignity, enterprise, vigor, and stability of the Federal government, emphasizing designs that embody the finest contemporary architectural thought.” Further, the G.S.A. is explicitly committed to “incorporating principles of sustainable design and energy efficiency into all of its building projects.”

Design work began in earnest in September, 2000. Broadly understood, the design of the new San Francisco Federal Office Building grew and evolved around three primary organizing concepts:

- the design of a building that offers dramatically reduced energy consumption through the integration of architecture and sustainable engineering principles;
- the creation of office environments that influence the productivity and health of the working population through natural ventilation, operable windows, and daylit interiors;

- the redefinition of the circulation and vertical movement paths in the building, using innovative elevators, three-story sky lobbies, and compelling stairways to promote walking throughout the building.

Considered together, the principles that have guided the design will yield significant operational and life-cycle cost benefit. Together with the G.S.A., the design team recognized the importance of a developing a flexible, intelligent, efficient, aesthetically significant building, one that serves the needs of the Federal government for generations to come.

The Potential

With a site located in downtown San Francisco, California, the temperate outdoor air temperatures (the monthly mean maximum temperature for September, which is the hottest month, is 75°F) prompted early discussions within the design team about the possibility of a naturally ventilated building. A study into the wind climate showed a strong prevailing wind condition from the west-northwest.

Given the favorable climatic conditions, the architectural team did further research into the occupant-perceived benefits of naturally ventilated buildings. These benefits have been clearly recognized by architects, engineers, facilities managers, and building owners in recent years. The expected advantages of by naturally ventilated buildings include increased worker productivity, lower turnover in the workforce, and fewer health issues, in contrast to the documented ventilation problems with sealed building envelopes. Additional benefits are expected to accrue from the extensive daylighting that has been included in the final design of the building.

The Implications

Building on the inherent climatic potential, the benefits to the occupants, and the potential to reduce energy use, the team moved forward with a careful and deliberate investigation into the implications of designing a naturally ventilated office building in a society that is used to fully air-conditioned ones. The issues included:

- the need to clearly explain intent and obtain early and strong client support for the organizing principles;
- the need to address the security and life-safety concerns associated with operable façade elements;
- the need for an integrated approach to design involving the architects, mechanical engineers, structural engineers, curtain wall consultants, electrical engineers and lighting designers;
- the need to embed the architectural language of the building within the mechanical and structural engineering concepts, inextricably binding each element of the building;
- the need for a radical change in interior space planning in order to enhance the natural ventilation cross-flow potential;
- the need to understand the most recent research into perceptions of comfort in naturally ventilated buildings and to involve specialist simulation modelers in the prediction of internal temperature and air speed conditions;

- the need to change the traditional paradigm that separates architectural design from interior design, since the design characteristics of the office furniture will have a direct bearing on the performance of the natural ventilation.

Client Support

With eight different federal tenant agencies involved, the team faced a considerable challenge in communicating the ideas behind the building to a wide variety of users, many with competing visions of how the new building should operate. Early in the process, key individuals in each agency were identified and included in substantive working sessions on the design concept. In this way, the architect and engineers were able to anticipate issues about the flexibility of the building, become familiar with the management problems that are associated with new construction and commissioning, and understand the very real concerns that the agency managers had about maintaining proper comfort levels in the building. Through these meetings, tenant representatives came to understand and appreciate the clear benefits that would be provided through the natural ventilation design.

While these detailed client meetings were taking place, the team also endeavored to communicate the detailed evolution of each component of the building to the owner. Review sessions with key G.S.A. engineers in the approval process for each discipline were undertaken to ensure that the natural ventilation concept was emerging in an open, engaged atmosphere. At each juncture in the approval process, the client was also kept informed of the overall energy consumption projections. In this way, the overarching goal of producing a highly efficient building was continually highlighted as a critical component of the process, helping to ensure the eventual approvals required for the project to proceed.

Security and Life-Safety Issues

Having the support of the General Services Administration for the principle of natural ventilation in this building on this site was instrumental in allowing the team to move forward with specific issues, including security and life safety. As with all buildings built under the aegis of the G.S.A., this federal office building is required to establish a “hard” (i.e., impenetrable) perimeter at the base of the building. Additionally, all outside air intakes into the building are well removed from easy access and all structure is designed with blast-resistance in mind. Despite the appeal of a building that could open up in response to the environment, security concerns mandate that the lower, more vulnerable floors be completely sealed. Thus, to achieve natural ventilation, a high-rise building was proposed with natural ventilation as the primary means of cooling on levels 6-18 and full air-conditioning on the lower levels.

This high-rise solution triggered a different set of challenges in the form of the smoke control code for high-rise buildings. The current Uniform Building Code and National Fire Code promote the compartmentalization of high-rise buildings in order to contain the generated smoke within the fire zone itself. This strategy is often accomplished by using the air conditioning system fans to pressurize adjacent zones with dedicated extract of smoke from the fire floor. A naturally-ventilated building with operable windows, then, presents a problem in that there is no air-conditioning system to assist with pressurization. Moreover, there are operable windows in the façade itself that may allow smoke to migrate up the exterior of the building.

In response to this challenge, the motorized window actuators are supplied from the emergency power circuit to close the windows in the event of a fire. Secondly, low voltage hold open options for the manual windows are currently under investigation, with gravity-driven closure upon loss of power to the electromagnets. Last but not least, the trickle vents are located at the floor slab, with very small openings. It is not currently anticipated that the amount of smoke leaving the fire floor through these vents would be significant enough to be detrimental to the air quality in the adjacent floors.

The final question in the life-safety category relates to the provision of minimum outside air for the internal areas of the 20 m (66') wide floor plate. The plan width was so designed on the assumption that the 6m (20') closest to the perimeter would be naturally ventilated, in keeping with industry's understanding of the penetration distance for single-sided natural ventilation, as exemplified by the current practice in California's Energy Code that allows a space to be considered naturally ventilated only if every part of the space is within 6m (20') of an operable element in the façade. Since the structural cores themselves would be on the order of 6m (20') deep for a high-rise building of this height, the floorplate naturally divided into two strips of naturally ventilated zones along the perimeter, separated by a spine of enclosed conference rooms, offices, restrooms, and break areas, which would have a constant supply of mechanical ventilation to ensure indoor air quality.

Integrated Design and Embedded Architecture

The design team sought to work in an environment of extremely close collaboration, challenging design assumptions across ALL disciplines in order to derive a thoroughly integrated solution, augmenting the emphasis from Jones and West (2001) regarding the “highly cooperative effort from the architect and indoor environmental engineer.” In fact, this multi-disciplinary type of intimate interaction is essential to the realization of a successful naturally ventilated building, as each discipline's design proposals have an impact on all the other disciplines in a cascading fashion. For instance, one decision about glazing that allows more light into the building might also simultaneously increase the solar gain to the point where the cooling from outside air alone will not be sufficient to keep indoor conditions comfortable. This would cause the mechanical engineer to introduce an air-conditioning system, which would then add electrical load on the building. On this project, this conflict was identified early in the process, acknowledging that high solar gains through the glass of the southeast façade would not only be uncomfortable for the occupants but may serve to deplete the thermal mass of its charge during the morning hours through long-wave radiative exchange between the warmed low level surfaces and the night-cooled thermal mass above. Thus the exterior shade was introduced not only to provide solar protection but also to allow for a form-based visible architecture with a standard repeatable floorplan. Additionally, fins perpendicular to the northwest façade were introduced to intercept direct solar radiation during the afternoon hours when the sun would otherwise fall on the glazing simultaneous to the peak outdoor air temperatures.

In another example of multi-disciplinary integration, the structural system in the main tower employs an upstand beam—non-standard in most concrete construction. However, a downstand beam in the same perimeter location would effectively detach the airflow from the slab during the night pre-cooling and lessen the effectiveness of the thermal mass (see **Figure 1**). In a similar manner, the downstand beam was disrupting the penetration of daylight from the façade. With the improved penetration of daylight as confirmed by the lighting consultant's daylighting

analysis, all perimeter zones could be designed with daylighting controls to dim the ambient artificial lighting whenever possible, allowing individuals to control a limited amount of local task lighting when performing tasks requiring more visual acuity.

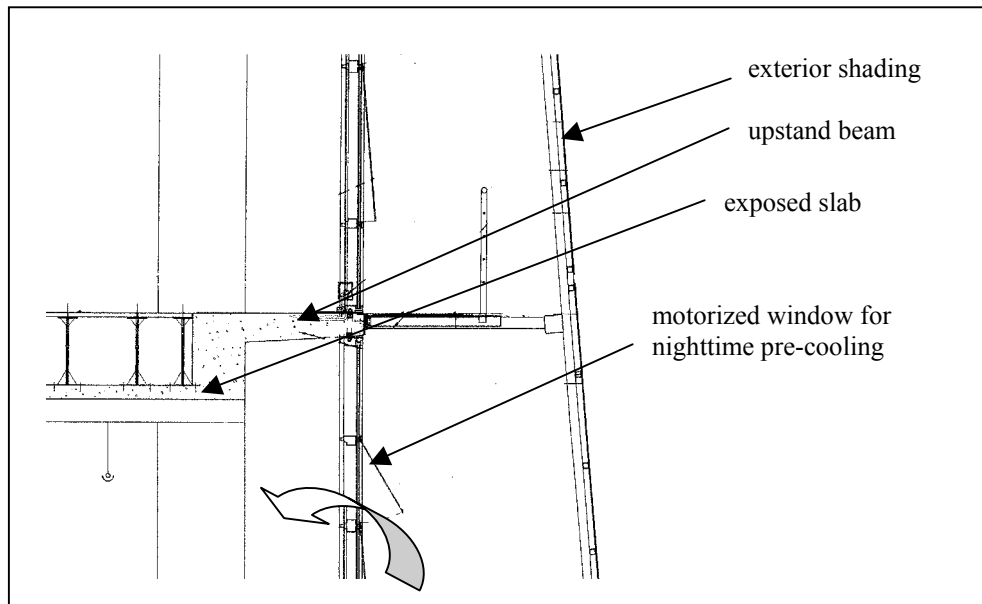


Figure 1. Section through slab/façade detail.

Furthermore, a useful byproduct of the upstand beam approach is the creation of an underfloor plenum. With removable floor tiles above, the plenum offers flexibility in the routing of telecommunications and electrical power conduit, easy access to the main piping routes, and space for underfloor air distribution in the lower sealed floors of the building and at the central spine of enclosed offices at each naturally ventilated floor. This underfloor air distribution scheme at the upper floors meant that the lid ceilings of the enclosed offices could remain thin, thereby creating a gap through which the two naturally-ventilated sides of the building could experience cross-flow under favorable wind conditions and the full slab could be pre-cooled in the nighttime purge of structural heat. The use of natural ventilation for nocturnal pre-cooling and the factors influencing performance are discussed by Martin and Fletcher (1996) and by Kolokotroni (2001).

A last example of integrated design and embedded architecture involves the sophisticated use of the multi-part window wall at the naturally ventilated areas. Besides the straightforward coordination to meet the glazing performance necessary for the comfort and lighting requirements, the curtain wall designer also integrated window actuators into the mullions and trickle vents at the base. Moreover, the architect and window wall consultant worked with the mechanical, electrical and structural engineers to develop a set of details that would allow the following “clean” window wall aesthetic:

- finned tube heating convectors mounted in the curtain wall mullion depth with dedicated pipe-bypass areas built into the mullions to minimize the visibility of piping, but maintaining proper access for servicing;

- conduit and pull-boxes integrated into the mullion system to allow a hidden route for electrical power wiring and low-voltage control wiring to the motorized window actuators;
- dedicated trenches and sleeves at each column bay within the structural slab to allow for piping and conduit to pass from the underfloor plenum area to the perimeter curtain wall zone.

Throughout the process, the team sought to continually strengthen the owner's perception of the building as an "integrated design," one that binds the architectural, engineering, and urban design goals tightly together. Most significantly, the architectural aesthetic has been intertwined with the engineering decisions made to minimize energy use. This approach was explicitly engaged to deter the possibility that the sustainability goals be abandoned at a later point in the design process through value engineering. Two rigorous value engineering sessions with independent peer auditors were completed during the design development phase; these reviews have confirmed the intelligence of this initial strategy.

Changes to Interior Space Planning

For the client/user group, the most challenging initiative in the design of the building has been the revision of the rules for the interior space planning. In order to enhance the benefit of the natural ventilation scheme in the tower, all individual offices at the perimeter of the floorplate have been eliminated, with open work stations lining the window walls on the southeast and northwest walls. All closed offices, conference spaces, and other private environments have been located along a central spine of each floorplate. This arrangement of interior spaces required detailed discussion with the client and tenant agencies about the inherent tradeoffs between two opposing realities: traditional hierarchical office culture on the one hand; fresh air, occupant control, and daylit interiors on the other. Finally, it is important to note that those agencies with intensive computer use or requiring air-conditioning are located in the sealed lower floors of the building.

Perception of Comfort

Natural ventilation is an umbrella term that usually refers to an airflow scheme in which air is provided directly from outdoors into an occupied space for any one or all of the following purposes:

- minimum ventilation: the process by which outside air is provided to an occupied space to maintain a minimal level of indoor air quality;
- night purge of structural heat: the process by which "freely-cooled" nighttime air is intentionally allowed into the unoccupied building in order to reduce the surface temperature of exposed concrete thermal mass inside;
- thermal comfort: the process by which air flow creates an acceptable indoor environment, both by replacing hot indoor air with cooler outdoor air and producing enhanced heat transfer at the skin.

The first two uses of natural ventilation are fairly straightforward and have been mentioned earlier in this paper. The use of natural ventilation for the last reason—thermal comfort -- requires more elaboration as it requires the occupant to understand that, unlike an air-conditioned space, a naturally ventilated building does not automatically adjust itself to control indoor temperature to a fixed set-point.

Thermal comfort in fully air-conditioned buildings is usually calculated using a static model. Such a model defines one thermal comfort temperature, referred to as a neutral temperature, as a quantifiable standard of comfort, independent of the building's location and climate. For example, the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE, 2001) defines "... standard specified conditions or comfort zones where 80% of sedentary or slightly active persons find the environment thermally acceptable." Recently, however, it has been argued (Brager, 2000) that "The standard was originally developed through laboratory tests of perceived thermal comfort, with the limited intent to establish optimum HVAC levels for fully climate-controlled buildings. However, in the absence of any credible alternative, Standard 55 is applied universally across *all* building types, climates and populations."

ASHRAE is currently in the process of extending its comfort standard (Standard 55) to include an 'adaptive model' for naturally ventilated buildings. The model is based on a large dataset of field observations that showed that "occupants of naturally ventilated buildings appear tolerant of—and, in fact, prefer—a wider range of temperature" than their counterparts within fully air-conditioned buildings. Of particular interest is that "behavioral adaptations, such as changes in clothing insulation or indoor air speeds, could account for only half the observed variance in thermal preferences. . . this suggested the rest of the variance was attributable to psychological factors. Chief among these was a relaxation of thermal expectations, possibly because of a combination of high levels of perceived control and a greater diversity of thermal experiences in the building." (Brager and de Dear 2000)

The design team proposed to the General Services Administration that the naturally ventilated portions of the new Federal Office Building should have design criteria in compliance with the proposed adaptive model, which links the indoor comfort temperature to the mean monthly outdoor air temperature, as shown in **Figure 2**.

Therefore the design of the natural ventilated areas within the San Francisco Federal building uses the adaptive model as the design criteria and will attempt to limit the range of indoor comfort temperatures to the 80% acceptability limits shown in **Figure 3**. The upper limit on the 80% acceptable range is 79-82°F for the cooling season (April 1-October 31).

Note that the 'comfort temperature' used in the standard is the indoor dry bulb rather than a composite temperature, such as operative temperature, that includes radiative effects. This is because the field measurements on which the adaptive model is based generally include dry bulb temperature but not radiant temperature.

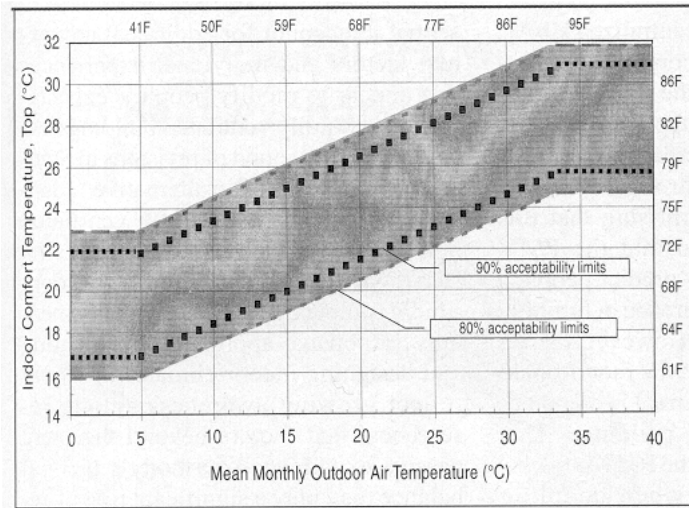


Figure 2. Proposed adaptive standard for comfort in naturally ventilated buildings (Source: Brager and de Dear 2000).

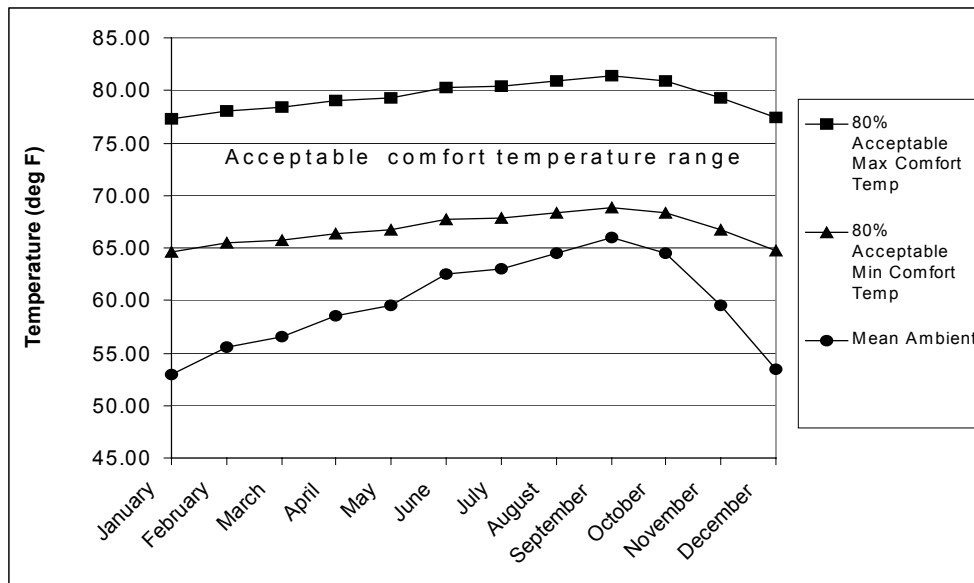


Figure 3. Monthly mean maximum, minimum and average temperatures for San Francisco and the 80% acceptability limits derived from Figure 2.

Assessment of Natural Ventilation Design Options

Having established the design target, it was then necessary to perform predictive simulations of indoor comfort temperature to see if the target was met. Lawrence Berkeley National Laboratory was commissioned to evaluate several natural ventilation strategies. In support of the conceptual design phase, several natural ventilation strategies were evaluated using a beta release of DOE's new building energy simulation program, EnergyPlus (Crawley et al. 2000), which includes the multizone air-flow model COMIS (Huang et al. 1999). The aim was to compare the ability of the different window configurations to maintain comfort during hot summer conditions. The strategies were:

- **wind only:** Continuous openings along both the NW and SE facades at the same height. Since the openings are at the same height, there is no buoyancy-driven flow.
- **internal stack:** Continuous openings at floor level on the NW façade and at ceiling level on the SE façade, which produces an internal stack; there are no wind effects.
- **internal and external stack:** Continuous openings at floor level on the NW façade, high openings into three story high chimneys on the SE façade, no wind effects
- **internal stack + wind:** Continuous openings at floor level on the NW façade and at ceiling level on the SE façade. The flow is produced by a combination of wind and internal stack effects.
- **internal and external stack + wind:** Continuous openings at floor level on the NW façade, high openings into three story high chimneys on the SE façade. The flow is produced by a combination of wind and internal and external stack effects.

A representative 9m section of one open plan office floor was modeled as a single thermal zone, including the appropriate internal and solar heat gains. The external chimney, when present, was modeled as a second thermal zone. A discharge coefficient of 0.5 was assumed for each opening (a conservative value that allows for pressure drop through the scrim) and pressure coefficients were estimated from data in Chapter 15 of the ASHRAE Handbook of Fundamentals (ASHRAE 2001). The different window configurations were simulated for the period April 1 to October 31 of the TMY2 composite weather year for San Francisco International Airport. A comparison of the meteorological conditions at the site to those at the airport indicated that summer-time maximum temperatures are a few degrees centigrade lower at the site, whereas minimum temperatures and wind speed and direction are essentially equal within the uncertainties of the information available. Use of airport data for cooling assessment is therefore considered to be conservative.

The predicted indoor temperatures were analyzed to produce **Table 1**, which shows the number of hours when the listed base temperature was exceeded during the occupied hours during the cooling season. When reviewing these data, it is important to recall that the upper limit design criterion is 79-82°F for the cooling season. The case of no ventilation is also shown for comparison. The main conclusions are:

1. Wind-driven night ventilation produces reasonable comfort conditions during the day for all but a few days of a typical year.
2. Internal stack-driven night ventilation resulting from low level openings on the NW and high level openings on the SE is less effective than wind-driven ventilation, resulting in internal temperatures on hotter days that are ~1°F higher than for the wind-driven case.
3. A combination of wind-driven and internal stack-driven ventilation produces a modest improvement in performance compared to the wind only case. The contribution of internal stack may be more significant if/where there is significant reduction in wind pressure due to shielding by adjacent buildings.
4. Addition of external chimneys does not improve the performance of the combination of wind-driven and internal stack-driven ventilation, and may be slightly counter-productive, due to the increased flow resistance caused by the chimney. In the absence of wind, addition of external chimneys helps the internal stack somewhat.

On the basis of this analysis, the design team decided that those funds which were allocated to the construction of the chimneys could be better used to provide high performance, double-glazed low-e glass on both northwest and southeast façade, thereby minimizing the heating loads and lending to higher level of indoor comfort through improved solar heat gain coefficient.

Table 1. Occupied Hours Above Various Base Temperatures

Base temperature (°F)	Wind only	Internal stack	Int & ext stack	Int stack + wind	Int & ext stack + wind	No ventilation
72	288	507	432	279	285	14561
75	80	118	103	76	76	8894
78	13	25	19	11	12	4284

Having established that the building in general has sufficient thermal capacity and natural ventilation openings to achieve the indoor temperature design criterion, the analysis proceeded to examine the building’s behavior on a worst-case day.

The indoor comfort temperature exceeds 78°F on six particularly hot days during the typical year, when the maximum ambient air temperature is in the range 86-95°F. **Figure 4** shows the predicted performance of the different strategies on one of these days, July 3, 1970, which was the third day of a sequence of three extreme days; the preceding two days had maximum temperatures of 86°F and 95°F. As a result, the building was not significantly pre-cooled at the beginning of the occupancy period, as nighttime temperatures also remained high. The rise in internal temperature during the first eight hours of occupancy is limited only by the thermal capacity of the building, since the outside temperature is too high for ventilation to be useful. The cases in which the wind is supplemented by internal or external stack effects have temperatures that would not easily be distinguished from the wind only case in **Figure 4** and have been omitted for clarity. Similarly, the internal plus external stack case has been omitted since it is difficult to distinguish from the internal stack case.

The version of EnergyPlus that was used in the preliminary assessment was a relatively early version and a number of ‘bugs’ have subsequently been found in the program that affect the absolute prediction of the space temperatures used to generate **Table 1** and **Figure 4**. However, subsequent studies of the sensitivity of the space temperatures to the ventilation rate confirm the basic conclusion of the preliminary assessment, i.e., that the airflow rates generated by wind pressure could be substantially reduced before the ventilation rate became the limiting factor in performance.

In support of detailed design, a more detailed simulation model was developed, which included the following features:

- separate zones for the open plan work areas on the NW and SE sides of the floor;
- an average vertical clearance between the top of the enclosed ‘cabins’ and the underside of the exposed ceiling slab of 0.5m;
- two operable openings on each façade, one at desk height (0.8m) and one at ceiling height (3.3m), the open aperture of each opening being restricted to 100mm;

- pressure coefficients, measured in a wind tunnel, for a location in the tower selected to have a low wind pressure difference between the NW and SE facades;
- approximated treatment of the angular dependence of the optical transmission of the scrim on the SE façade;
- a glazing system consisting of an outer layer of 6mm glass with a low emissivity, spectrally selective coating and an inner layer of blast-resistant, laminated glass, the system having a visible light transmission of 0.6 at normal incidence and a Solar Heat Gain Coefficient of 0.3.

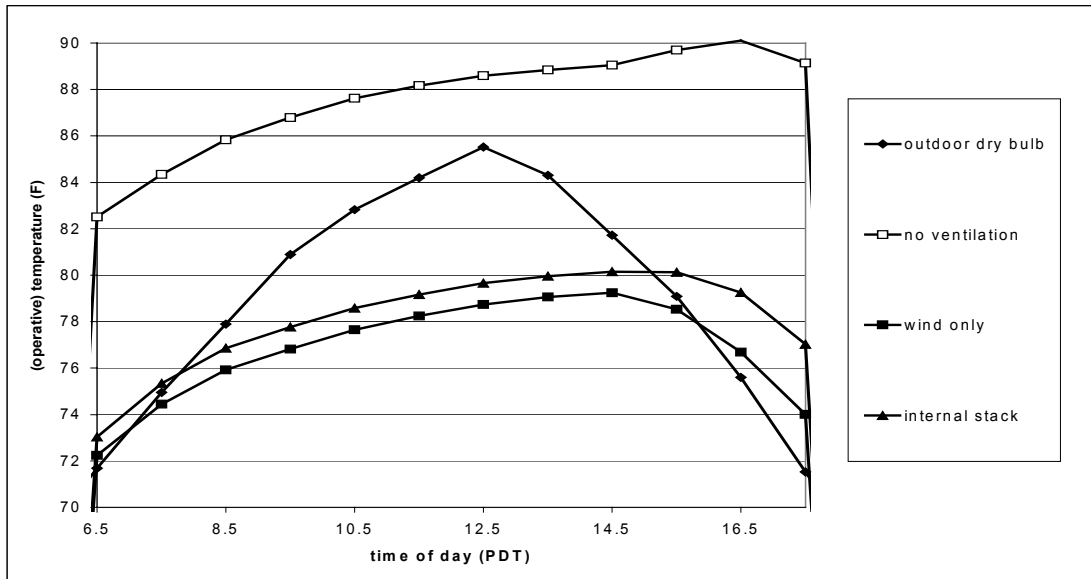


Figure 4. Relative performance on the third of a sequence of hot days.

The performance trends under very hot weather conditions predicted by the detailed model are quite similar to that predicted by the initial model, but the current version of EnergyPlus (V1.0.0.1, Build 10), predicts that there will be ~38 weekday hours per year above 78°F.

The performance of the natural ventilation system is limited by the amount of exposed thermal capacity and the magnitude of the daytime gains, particularly solar gains. The major difference between the preliminary model and the detailed model is the treatment of the enclosed cabins. A major effect of the cabins is to largely decouple the thermal capacity of the exposed slab above the cabins from the open plan spaces and hence reduce the effective thermal capacity by ~33%. Compensating improvements have come from an improved glazing system and treatment of the off-axis transmission of the scrim.

There are indications that reducing the transmissivity of the glazing system would improve cooling performance under very hot weather conditions without a significant adverse impact on the daylighting. However, this issue needs to be considered in the broader context of the daylighting in the space and the possibility of using dimming controls for the lights above the inner row of workstations on the NW side. The current models assume operable blinds on the NW façade; other options for solar control on the NW façade will be considered within the broader context of the lighting and daylighting aspects of the design.

Conclusions and Future Work

Building on the current results that show comfortable conditions for the vast majority of occupiable hours in the year, more detailed modeling, in the form of the computational fluid dynamics (CFD) currently under way. Coincident with this study will be a review of the most recent EnergyPlus model's behavior, as it will be providing nominal surface temperature boundary conditions for the CFD. This further set of analyses is intended to address the question of ventilation effectiveness in the workstations on the leeward side of the full height service cores and air velocities at the windward side façade openings. The detailed air-velocity and temperature distributions in these specific areas, when taken with the radiant temperature data from EnergyPlus, will be able to give the design team an overall picture of the acceptability of the naturally ventilated environments in these particular "worst-case" local zones.

Additionally, a CFD sensitivity analysis of internal air velocities versus various outdoor wind speeds will allow the control algorithm for the motorized windows to be developed in the next phase of the design. Current explorations include such features as:

- monitoring differential pressure across the floor width in order to select the temperature sensed at the current lee-side of the cabin areas as the dominant feedback.
- using the National Weather Service Internet forecasts to provide a prediction of the next day's peak temperature as an input to the window control sequence for nighttime purge of heat from the thermal mass
- dedicated trenches and sleeves at each column bay within the structural slab to allow for piping and conduit to pass from the underfloor plenum area to the perimeter curtain wall zone.

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