A STUDY OF PROPERTIES OF THE CAP DOUBLE-SKIN BUILDING FACADE

Center for Energy Research / Education / Service
CERES
Ball State University - Spring 2003
Robert J. Koester, Director
Steven R. Cook, B. ARCH May 2003
Robert J. Patton, B. ARCH May 2003

Figure 1.1. Interior view of the solar chimney on the College of Architecture and Planning (CAP) Building.
(Photo by Robert J. Patton, 2003)

A Study of the CAP Double-Skin Building Facade

Ball State University
College of Architecture and Planning
Muncie, Indiana

Table of Contents

Figure 3.A. College of Architecture and Planning Building at Ball State University. (www.bsu.edu, 2003)

Participants

Ball State University

Center for Energy Research / Education / Services (CERES)
Robert J. Koester, Director
Jeff Culp, Environmental Systems Advisor
Alfredo Fernandez-Gonzalez, Environmental Systems Educator
Robert A. Fisher, CERES Resident Fellow

Facilities and Planning
Danny Cox, Environmental Control/Chill Plant Supervisor
David Bartle, Technical Resources Manager
Thomas Frisbee-Fulton, Director of Facilities Planning

College of Architecture and Planning
Steven R. Cook, Undergraduate Student
Robert J. Patton, Undergraduate Student

Acknowledgements

This research project could not have been realized without the assistance of many professionals. **Bob Koester**'s expertise in environmental research was fundamental to the success of this project with his guidance serving as an incredible resource. **Jeff Culp**'s knowledge and experience with scientific data collection and analysis was critical to the development of the tests performed on the CAP solar chimney. **Bob Fisher** and the **CERES staff** provided essential technical critiques that helped establish the performed research tests. The variety of testing phases required the CAP building's solar chimney to be manipulated on a regular basis and could not have been accomplished without the cooperation and assistance of **David Bartle**. **Alfredo Fernandez-Gonzalez**'s research project "Mean Radiant Temperature (MRT), Human Comfort and Passive Solar Buildings" provided crucial outdoor climatic data to analyze the performance of the solar chimney. Finally, **Don Sporleder**'s insight into the design of the CAP addition provided a much needed understanding of the full scale test model. For their continued assistance and dedication to environmental design, research, and education, we cannot thank them enough.

This study came about as a secondary phase to an investigation that was completed during the fall semester of the 2002-2003 academic year at Ball State University. A 1"=1'-0" scale model was constructed to demonstrate the behavior of three different types of double-skin facades: the full height, floor to floor, and natural ventilation systems. The model was tested using a 16,000 watt sun simulator and a smoke gun to generate the natural stack effect that the double-skin technology relies upon. Although the three schemes generally operated as intended, the recorded air velocity readings for the three schemes provided insight into some of the construction details that are vital for the schemes to be effective.

Figure 5.1. Scale Demonstration Model
(Photo by Robert J. Patton, 2002)

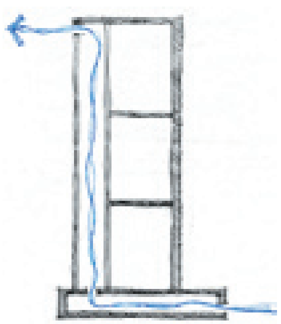


Figure 5.A. Stack effect sketch.
Diagram by: Robert J. Patton

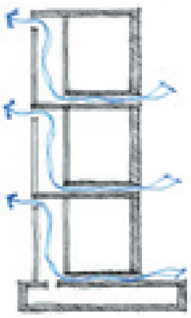


Figure 5.B. Floor to floor sketch.
Diagram By: Robert J. Patton

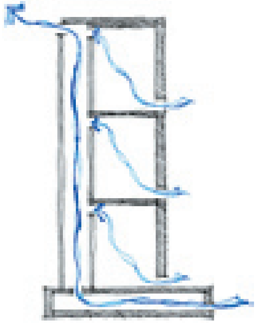


Figure 5.C. Natural ventilation sketch.
Diagram By: Robert J. Patton

The testing on the scale model was originally intended to record temperatures within each floor level, inside the cavity, and outside the model to track the effectiveness of the "temperature buffering" for which the double-skin building facades are designed. The small scale of the model, however, lead to inconclusive data on the temperature readings.

The College of Architecture and Planning (CAP) at Ball State University included a solar chimney in its 1981 addition. The solar chimney embodies the same principles that were tested on the scale demonstration model and was seen as an opportunity to test and analyze the temperature behavior of a double-skin building facade at a full scale, in real time.

Although this study began with the intent of continuing the previous investigation of double-skin operating schemes, the complexity of the CAP building's operations has lead beyond a study of general principles, to an investigation that includes an historical account for the building as designed, as built, and as operated. This study also looks at the intentions for the CAP building's solar chimney and indicates an analysis of its current and potential working conditions.

Figure 5.2. Sun Simulator
(Photo by Robert J. Patton, 2002)

History

Figure 6.1. Current North Facade.
(Photo by Robert J. Patton, 2003)

The addition to the College of Architecture and Planning (CAP) was the result of a design competition limited to Architects in Indiana. The program for the addition was based on consolidating the facilities for the Architecture, Landscape Architecture, and Urban and Regional Planning curricula into one building, providing additional space to accommodate anticipated student growth and for the support of multi-disciplinary programs of instruction and demonstration in the field of solar energy.[1] The competition required that the new facility use solar energy to partially heat the air and water required for the building as well as create a high degree of visibility for the total expression of the CAP Building.[2] The winning design entry was submitted by Crumlish/Sporleder and Associates. Their design scheme incorporated north and south facing glazed roofs that allowed natural light into all of the design studios while maintaining the view to the south quadrangle (Figure 6.A.). According to Don Sporleder, "numerous case studies influenced the multitude of natural operating schemes including a Moroccan courthouse."[3] Their design intent was to allow the CAP addition to maximize its use of natural ventilation in a variety of conditions. The jury chose the design for its "open, convivial nature of the interior, where one would be aware of the work and activities of others."[4]

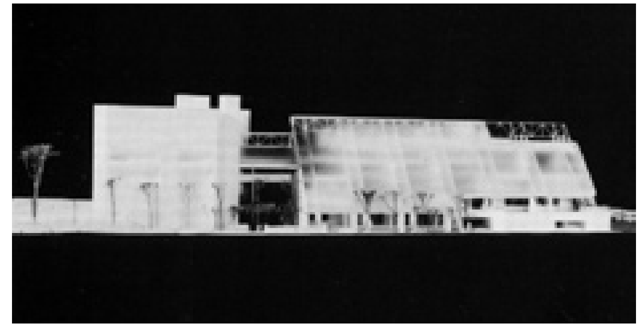


Figure 6.A. Winning competition model view from south.
(Crumlish/Sporleder and Associates, Indiana Architect, June 1981)

After the architects were selected, several changes were requested by Ball State University and the College of Architecture and Planning. Perhaps the most significant of the changes was the removal of the sloping roof on the north side of the addition. (Figure 6.1., 6.B., & 6.C.) In addition, the discovery of a high water table impacted the form of the building by necessitating that the basement level be raised one story, resulting in a taller building. Due to budget constraints, the vestibule on the south facade was cut out because at the time, it was not seen as a primary entrance.[5] Active solar equipment was deleted and transformed into a passive solar system which resulted in the development of the solar chimney.

Figure 6.B. Winning competition perspective view from north.
(Crumlish/Sporleder and Associates, Indiana Architect, June 1981)

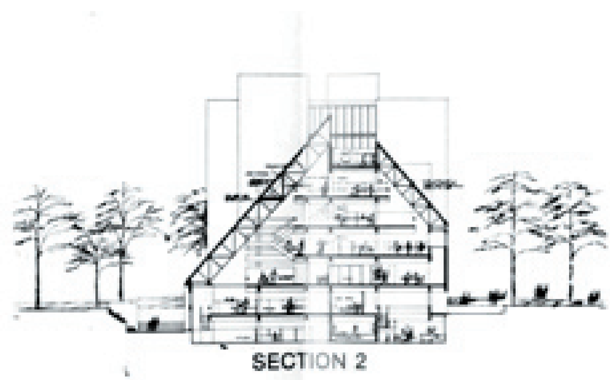


Figure 6.C. Winning competition building section.
(Crumlish/Sporleder and Associates, Indiana Architect, June 1981)

In the bid documents for the south slope wall, the solar chimney was proposed as an alternate in lieu of a single layer of thermally reflective glazing. (Figure 7.A.) The mechanical equipment for the addition was originally sized with the anticipation of solar gain through the single layer of glazing. This system, although functional, was declined by the university and as a result, the alternate bid solar chimney was selected. The mechanical equipment was then sized to operate under the anticipated extreme climatic conditions without reliance on solar devices or natural ventilation.[6]

Figure 7.A. Winning competition model.
(Crumlish/Sporleder and Associates, Indiana Architect, June 1981)

The solar chimney consists of three 27' bays that vertically span 4 stories at an angle of 52 degrees. The sloping wall is formed by deep trusses that support the inner and outer linings of the chimney. The outer layer is made up of thermal insulated glazing and the inner lining consists of a series of alternating panels of horizontal and vertical planes that stair step along the entire surface. The vertical planes comprise insulated glass windows that maintain the view to the quadrangle. The horizontal planes are made up of a two inch thick tectum deck for sound absorbency. Placed on top of these were tubes containing eutectic salts for energy storage. The effect of the alternating planes helps control glare and solar gain by limiting the passage of light to only the vertical planes. (Figure 7.1) Operable louver blinds were also installed inside of the cavity to control the natural light and resulting solar gain that can be absorbed in the concrete slabs of the atrium. By closing the blinds, the solar gains are contained in the air mass of the solar chimney. This air mass can be exhausted. (Figure 7.B.) The eutectic salt tubes helped maintain a stabilized temperature inside the solar chimney by absorbing and releasing energy as the solar radiation changes throughout the day. The horizontal planes include motorized dampers that work with the fresh air dampers at the base and top of the solar chimney to allow the solar chimney to change configurations and thus operate differently during the varying climatic conditions of the year.[7] (Figure 8.A.)

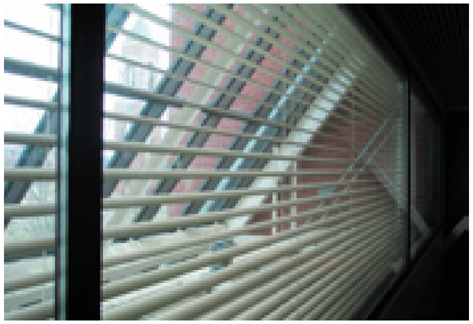


Figure 7.B. Motorized horizontal blinds.
(Photo by Steven R. Cook, 2003)

Figure 7.1. Interior of CAP atrium.
(Photo by Steven R. Cook, 2003)

The addition to the college of architecture and planning was designed to operate in three distinct configurations. During the summer, the solar chimney should be opened to create a stack effect inside of the chimney and exhaust solar heat gains from the cavity to prevent the overheating of the glass facade. During the winter months, the solar chimney should remain closed to maximize the heat gains within the cavity and create a buffer between the inside and outside temperatures. When conditions are favorable, natural ventilation of the building is made possible

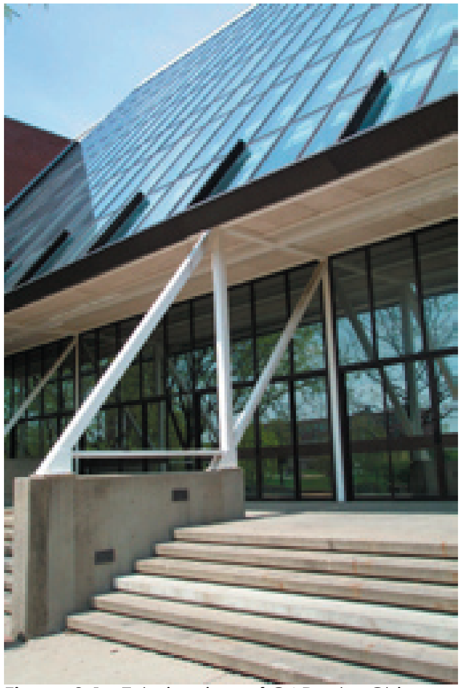


Figure 8.1. Exterior view of CAP solar Chimney.
(Photo by Robert J. Patton, 2003)

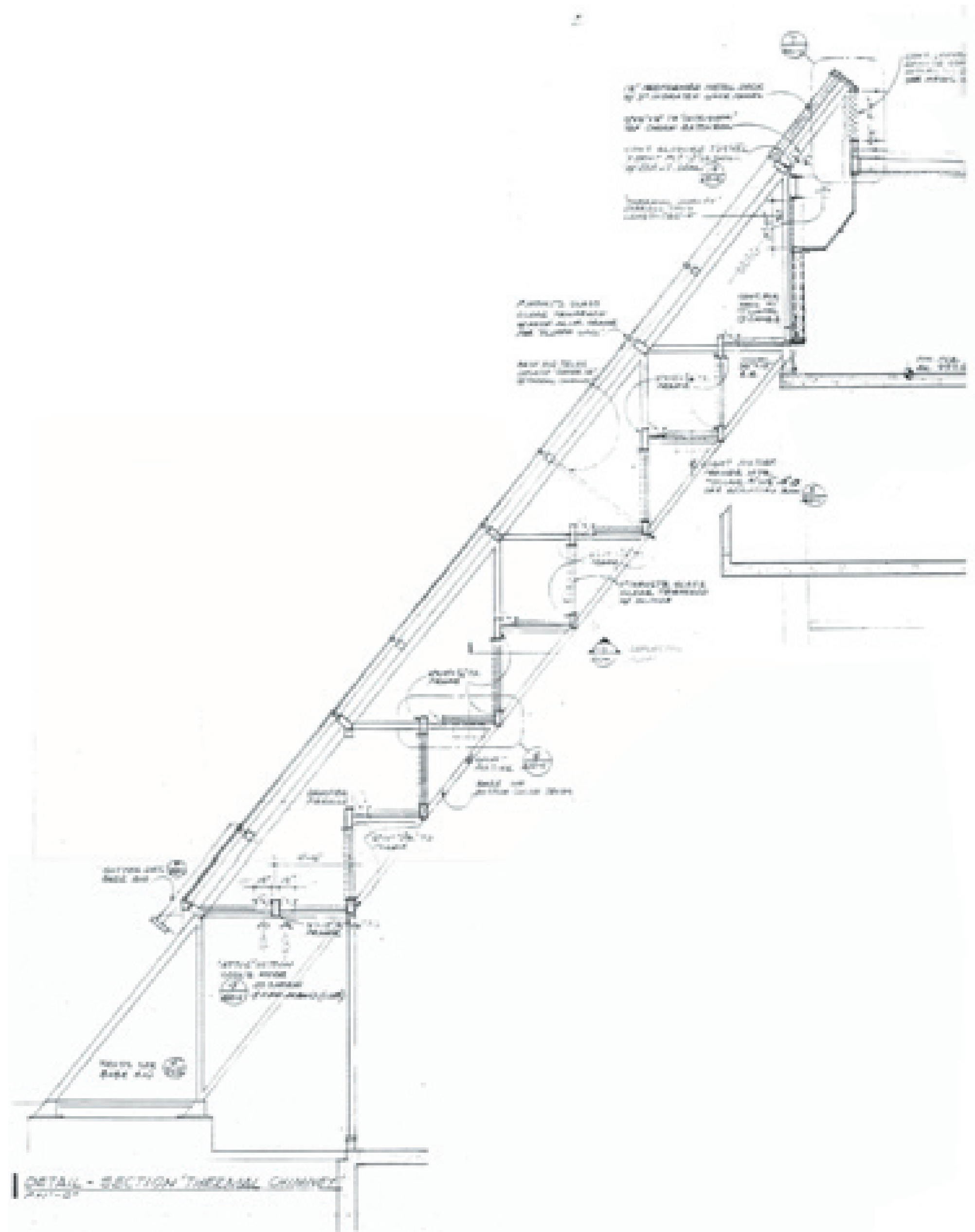


Figure 8.A. Detail section of CAP solar chimney .
(Crumlish/Sporleder & Associates, 1980)

by utilizing the operating sashes on the north side of the building, the dampers at each of the horizontal levels of the solar chimney, and the dampers at the top and bottom of the solar chimney. This operation method allows fresh air to be drawn in from the windows on the north side of the building, across the open studios, and exhausted through the stack effect by the solar chimney.

Over the building's life span, there have been considerable changes made that have affected the building's original operating schemes. First, the phase change material was removed due to leakage problems. Additionally, the operable windows on the north facade have been sealed due to strains on the mechanical system and misuse. (Figure 9.1.) Currently, the solar chimney remains in its closed position throughout the year and only functions as a thermal buffer; there is no system that coordinates between the mechanical and manual operation methods.

The Ball State Department of Facilities Management is currently planning on upgrading some mechanical equipment in the College of Architecture and Planning during the summer of 2003. The upgrade will bring the mechanical system online with the university-wide computer monitoring system that allows facilities management to monitor the performance of all campus buildings from a central location. This upgrade could be coordinated with the original operating intent and revitalize the capabilities of the solar chimney. In restoring the use of the solar chimney, educational opportunities will be available to students interested in passive building performance and computer controlled monitoring systems.

Figure 9.1. Permanently locked studio window.
(Photo by Steven R. Cook, 2003)

Based on the information that has been gathered about the design intent, as built condition, and as operated condition, it has been determined that portions of the design intent could be reactivated without changing the daily use of the facility. Although the original design included a mechanically controlled system, it also relied heavily on manual input for maintaining the appropriate operating condition. The Siemens software that Ball State University uses to monitor the mechanical systems in most campus buildings has the potential to replace the manual control component in the operation of the CAP building's solar chimney.

The four original operating schemes required operating louvers, vents, blinds, doors, and windows to maximize the use of natural energy (Figures 14.A., 15.A., 16.A., & 17.A.). Due to the modifications to the building over time, portions of the four original schemes can be resurrected to create two new operation schemes. The first scheme would enable the cavity of the south sloping glass to exhaust any heat gain that would collect on the inner skin of the facade during hot days and full sun (Figure 12.A.). The second scheme would allow the south sloping glass to act as a thermal buffer between the indoor and outdoor air temperatures (Figure 13.A.). These two systems only require minor modifications to update the system.

The major component of the upgrade would be the reactivation of the top and bottom louvers to enable the solar chimney to allow air to circulate through the cavity. The next component of the upgrade would involve the installation of sensors that would control the motorized blinds inside the solar chimney which not only reduce glare, but control solar gain. The reapplication of a thermal storage material within the double skin cavity would also maximize the use of solar energy. Each of these systems would be independently controlled while collaborating to increase the effectiveness of the building's natural energy performance.

(Footnotes)

[1] Indiana Society of Architects. "Design Competition Addition to the College of Architecture and Planning Ball State University." Indiana Architect. (Special Issue June 1981), p. 9.

[2] Ibid. p.9.

[3] Personal Interview with Donald Sporleder conducted on 2/7/03.

[4] Indiana Society of Architects. "Design Competition Addition to the College of Architecture and Planning Ball State University." Indiana Architect. (Special Issue June 1981), p. 13.

[5] Personal Interview with Donald Sporleder conducted on 2/7/03.

[6] Crumlish/Sporleder and Associates. "Energy Aspects of the New CAP Building on the Ball State Campus." July 12, 1981.

[7] Ibid.

1.) The CAP solar chimney is an effective design strategy that regulates and controls solar gains throughout the day.

2.) The activation of (A) top and bottom louvers and (B) motorized sun-shading blinds impacts the daily performance of the CAP solar chimney.

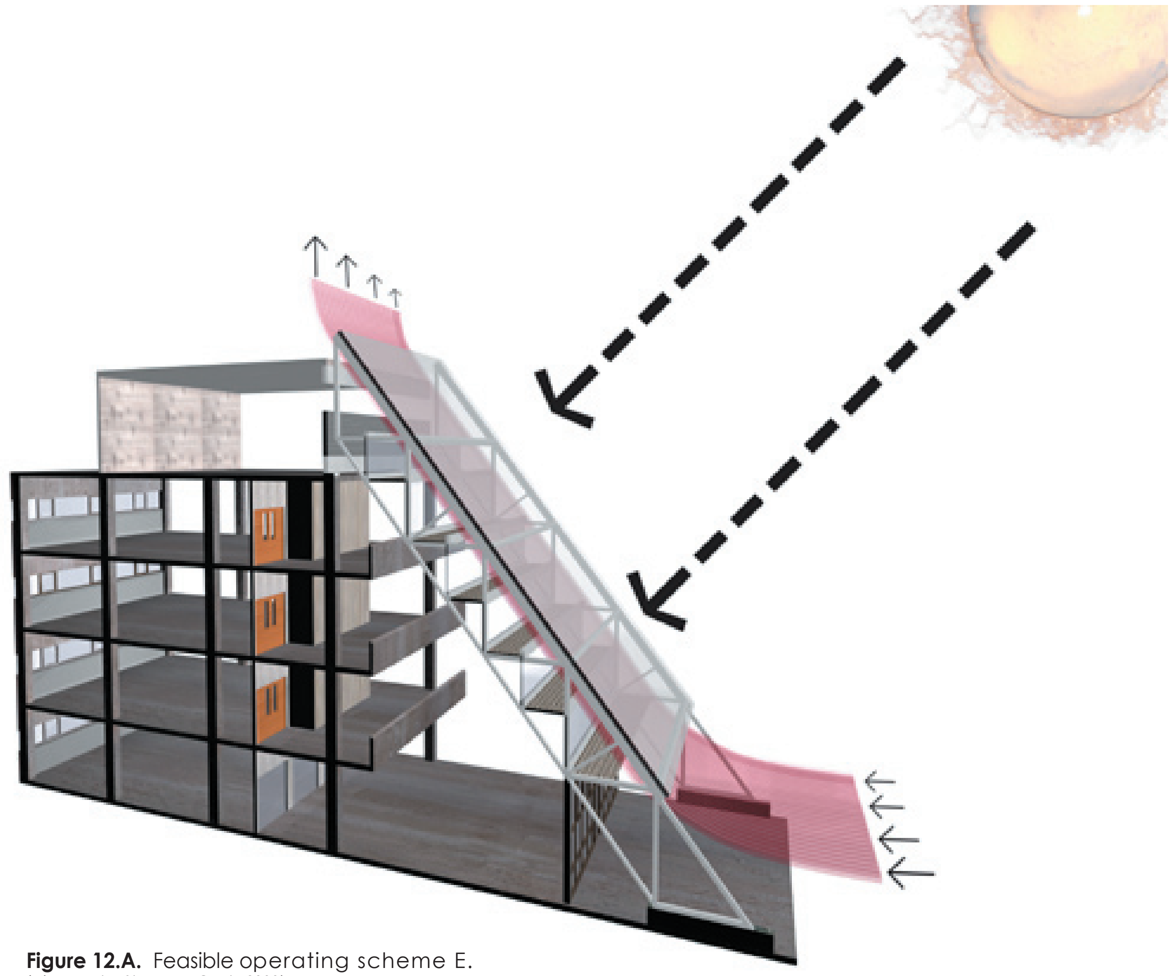


Figure 12.A. Feasible operating scheme E.
(Diagram by Steven R. Cook, 2003)

CASE A: <u>Typical Weather Conditions</u>
Spring, Summer, and Fall
(when the outdoor air temperature is higher than the intended indoor air temperature)

<u>Intended Operational Procedure</u>
Open Top Louvers
Open Lower Louvers

Opening the top and bottom louvers creates a stack effect inside the solar chimney and is able to exhaust solar heat gains. Exhausting these solar gains can reduce loads on the mechanical equipment for the building.

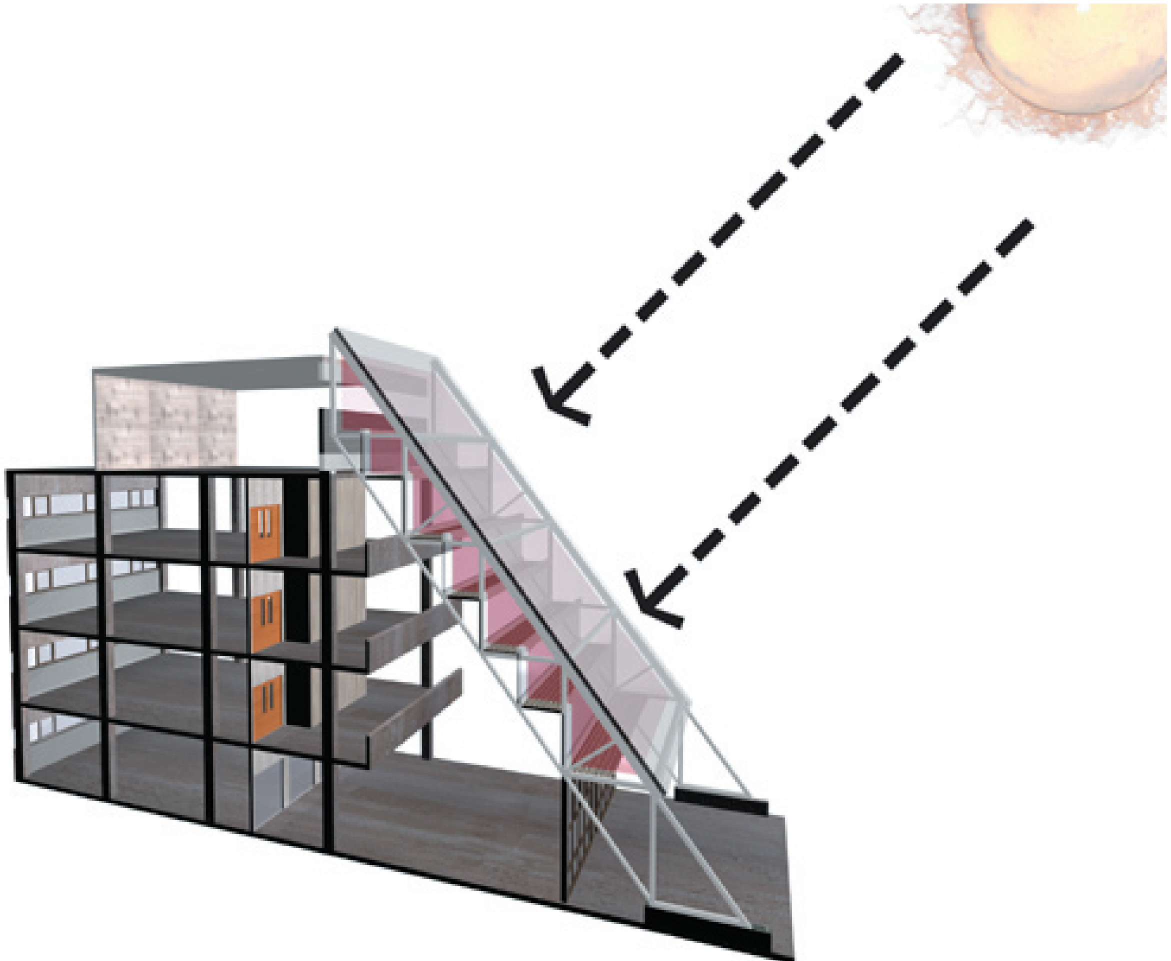


Figure 13.A. Feasible operating scheme F.
(Diagram by Steven R. Cook, 2003)

CASE B: Typical Weather Conditions
Fall, Winter, and Spring
(when the outdoor air temperature is lower than the intended indoor air temperature)

Intended Operational Procedure
Close Top Louvers
Close Lower Louver

When the top and bottom louvers are closed, the trapped volume of air can be heated by the sun to raise its temperature and create a buffer between the outdoor air temperature and the conditioned indoor air temperature. This buffering strategy can reduce loads on mechanical equipment for the building.

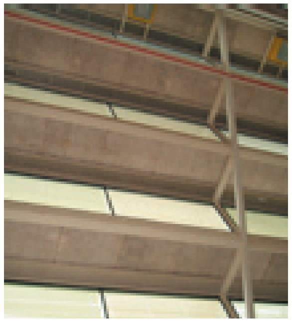
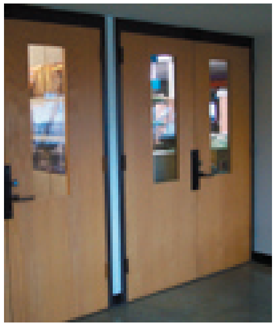


Figure 13.1. Atrium dampers are closed.
(Photo by Steven R. Cook, 2003)

Figure 13.2. All operable windows on the north facade have been bolted shut.
(Photo by Steven R. Cook, 2003)



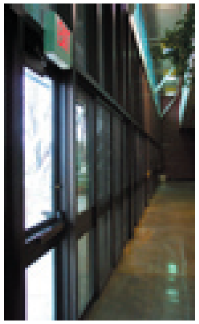
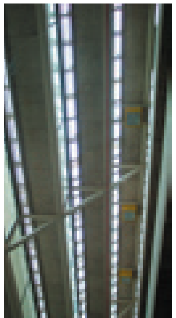


Figure 13.3. Studio doors cannot remain open for security purposes.
(Photo by Steven R. Cook, 2003)

Figure 13.4. Atrium doors are rarely, if ever, fully opened.
(Photo by Steven R. Cook, 2003)



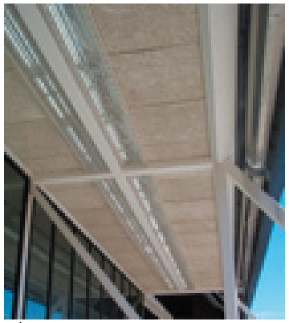


Figure 14.1. Atrium dampers are open.
(Photo by Steven R. Cook, 2003)

Figure 14.2. Top and bottom louvers are open.
(Photo by Steven R. Cook, 2003)

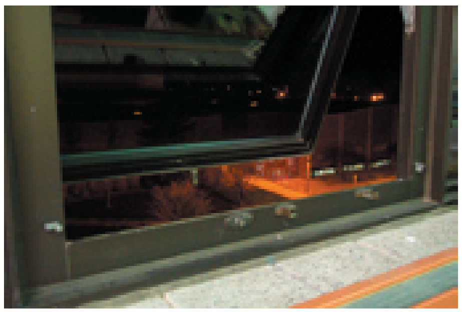
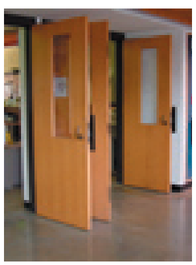


Figure 14.3. Operable windows on the north facade are open.
(Photo by Steven R. Cook, 2003)



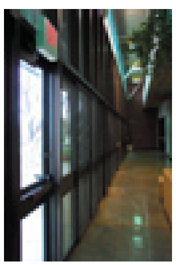


Figure 14.4. Studio doors are open.
(Photo by Steven R. Cook, 2003)

Figure 14.5. Atrium doors are closed.
(Photo by Steven R. Cook, 2003)

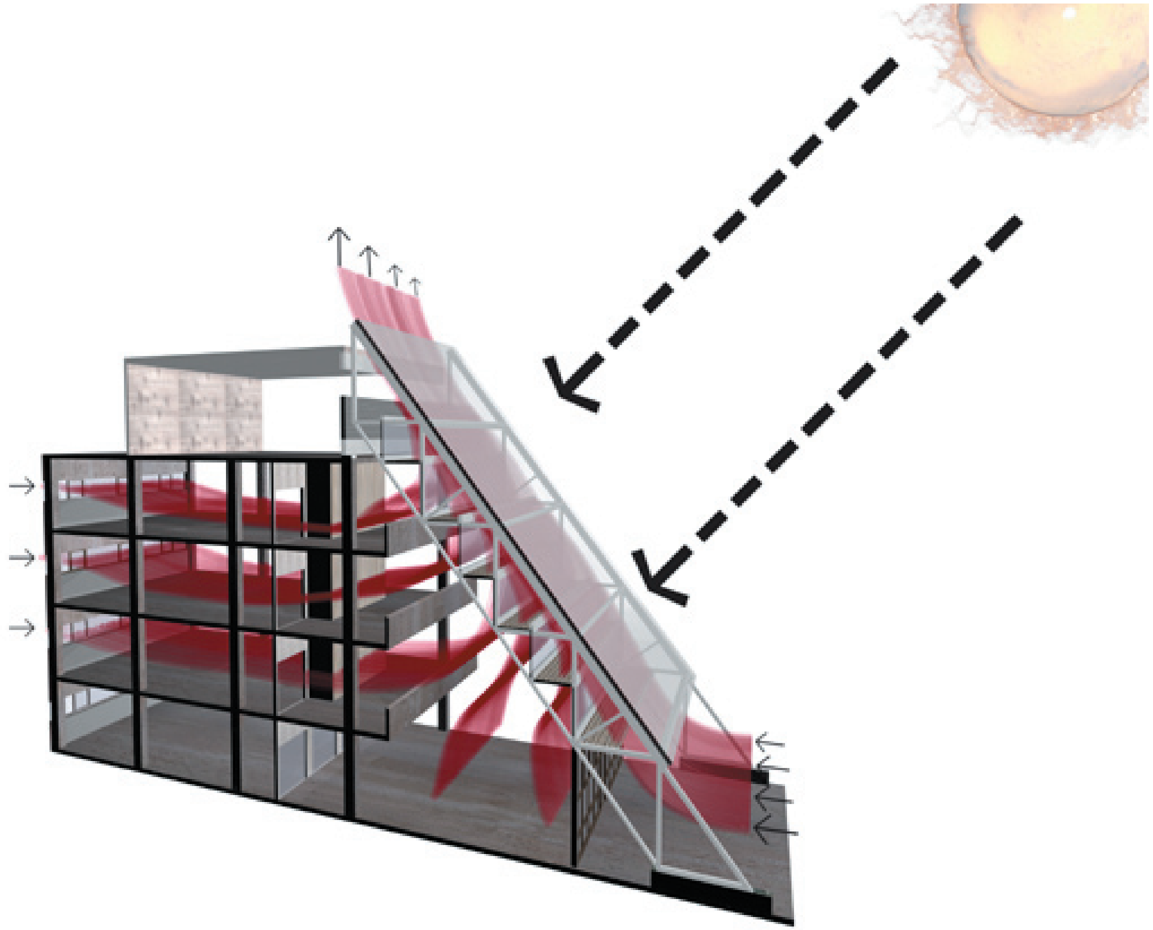


Figure 14.A. Natural Ventilation scheme A.
(Diagram by Steven R. Cook, 2003)

CASE C:

Typical Weather Conditions		Intended Operational Procedure
Temp.	48 - 80 degrees (Fahrenheit)	Open North Windows
Wind spd.	2.4 -22 MPH	Close South Doors
NO. Days	302 days/Year	Open Unit Dampers

A stack effect is created inside the solar chimney from the sun and is able to draw air in from the windows on the north elevation, across the studios, up through the individual stepped vents, and exhausted out the top louvers. This scheme can no longer work due to the operable windows being bolted shut and the studio doors being locked for security reasons.

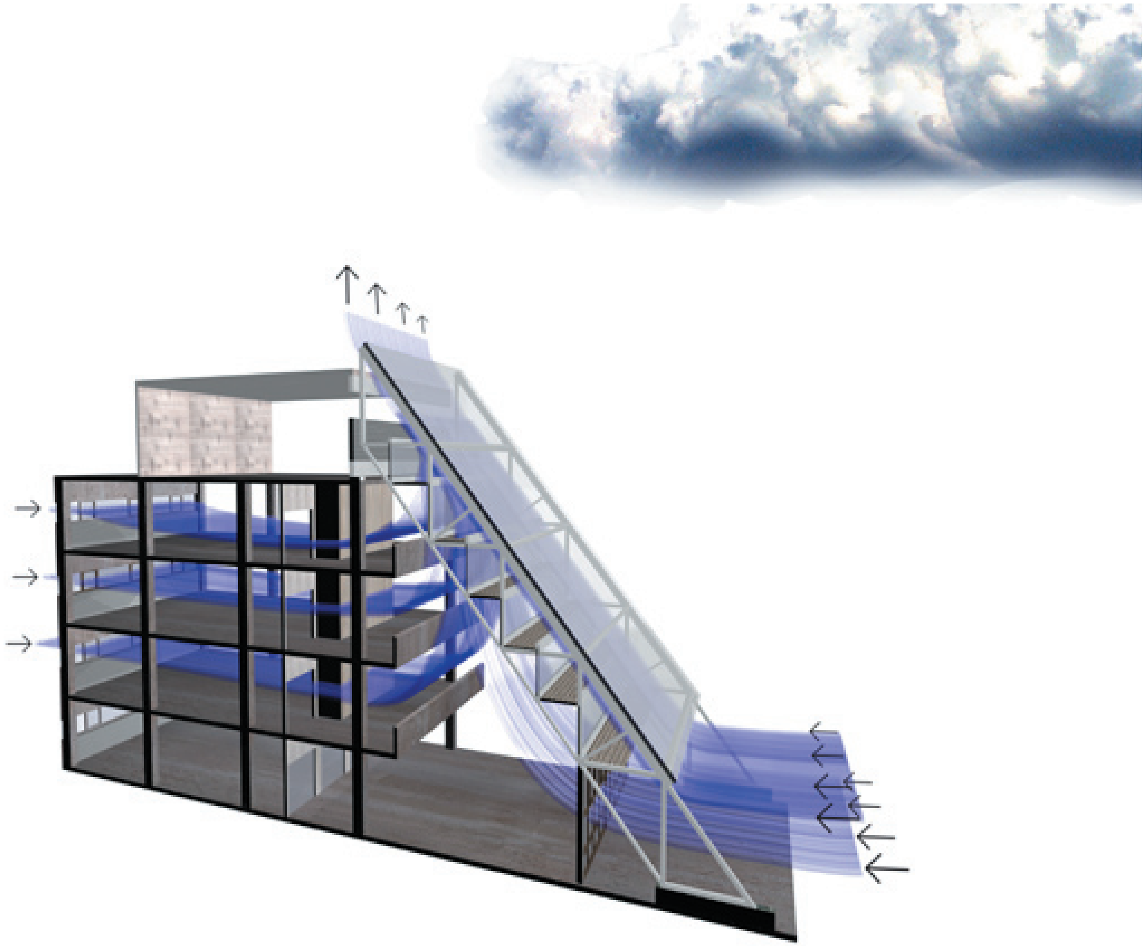
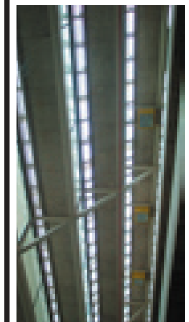


Figure 15.A. Natural Ventilation scheme D.
(Diagram by Steven R. Cook, 2003)

CASE D:

Typical Weather Conditions		Intended Operational Procedure
Temp.	48 - 80 degrees (Fahrenheit)	Open North Windows
Wind spd.	6 MPH. 5 Days/Year	Open South Doors
	10 MPH. 34 Days/Year	Open Lower Vent
	16 MPH. 149 Days/Year	Open Unit Dampers

A natural stack effect draws air in from both the north and south elevations and exhausts the air out through the solar chimney. This scheme can no longer work due to the operable windows being bolted shut, the studio doors being locked for security reasons, and the south atrium doors remaining in the closed position.



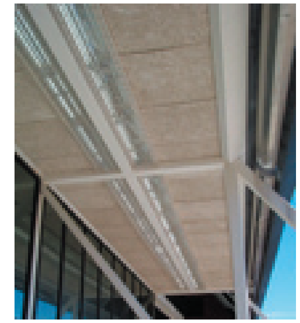


Figure 15.1. Atrium dampers are open.
(Photo by Steven R. Cook, 2003)

Figure 15.2. Top and bottom louvers are open.
(Photo by Steven R. Cook, 2003)

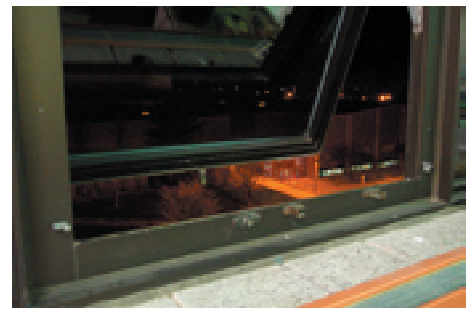


Figure 15.3. Operable windows on the north facade are open.
(Photo by Steven R. Cook, 2003)

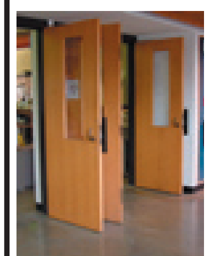
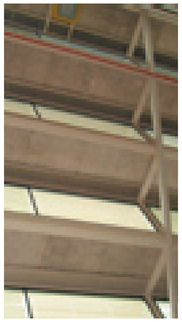


Figure 15.4. Studio doors are open.
(Photo by Steven R. Cook, 2003)

Figure 15.5. Atrium doors are open.
(Photo by Steven R. Cook, 2003)



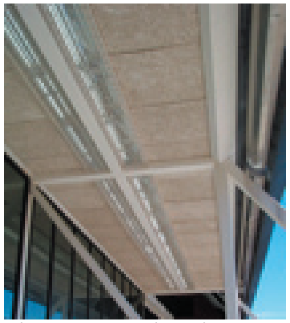


Figure 16.1. Atrium dampers are closed.
(Photo by Steven R. Cook, 2003)

Figure 16.2. Top and bottom louvers are open.
(Photo by Steven R. Cook, 2003)

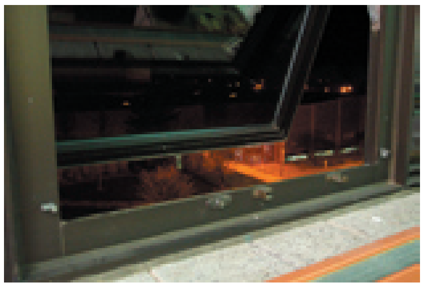


Figure 16.3. Operable windows on the north facade are open.
(Photo by Steven R. Cook, 2003)

Figure 16.4. Studio doors are open.
(Photo by Steven R. Cook, 2003)

Figure 16.5. Atrium doors are open.
(Photo by Steven R. Cook, 2003)

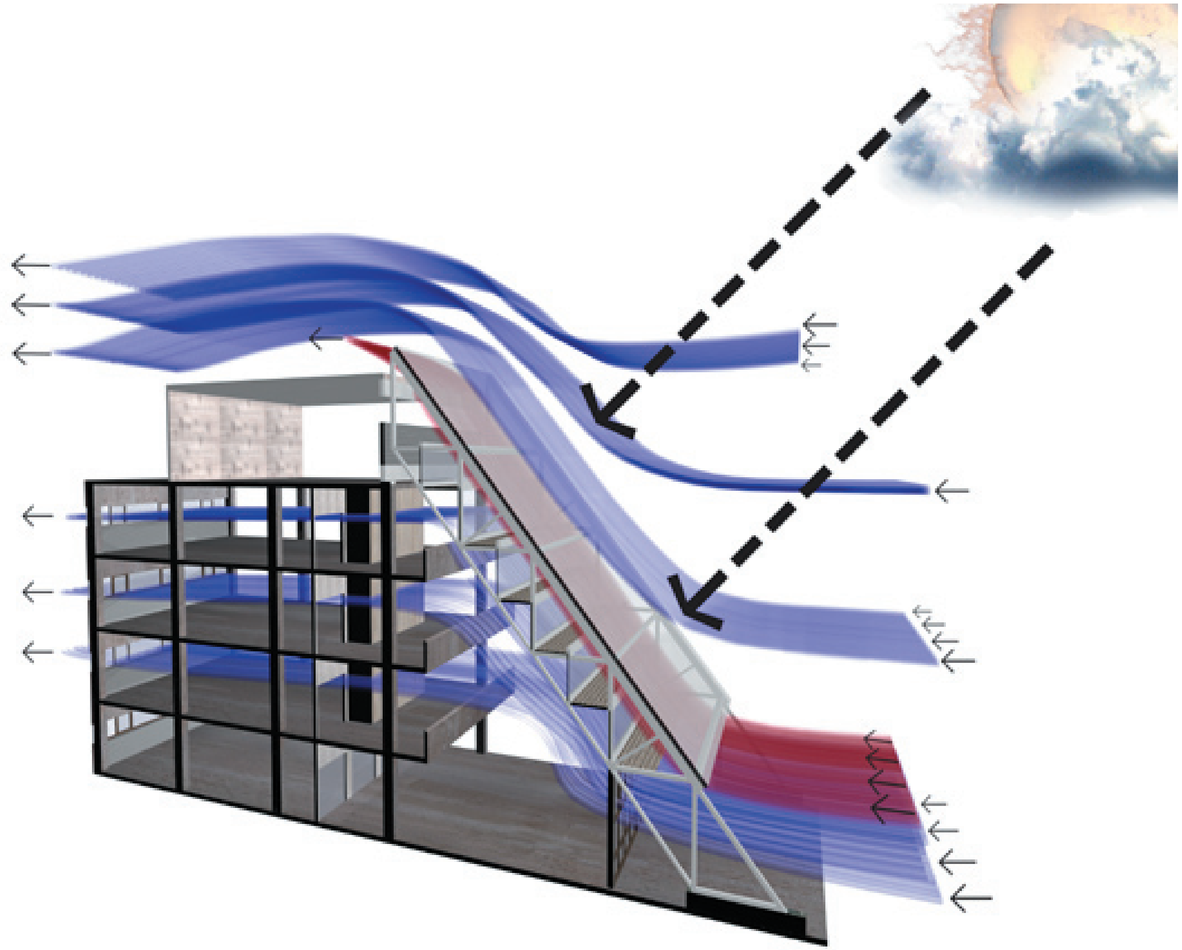


Figure 16.A. Natural Ventilation scheme C.
(Diagram by Steven R. Cook, 2003)

CASE E:

Typical Weather Conditions		Intended Operational Procedure
Temp.	48 - 80 degrees (Fahrenheit)	Open North Windows
Wind spd.	14 MPH (south)	Open South Doors
NO. Days	9 days/Year	Open Lower Vent
		Close Unit Dampers

The south wind creates negative air pressure and pulls air through the building from the south, through the atrium and studios, and exhausting on the north side. A stack effect is still created inside the solar chimney from the sun and is able to draw some air into the solar chimney to exhaust solar heat gains. This scheme can no longer work due to the operable windows being bolted shut, the studio doors being locked for security reasons, and the south atrium doors remaining in the closed position.

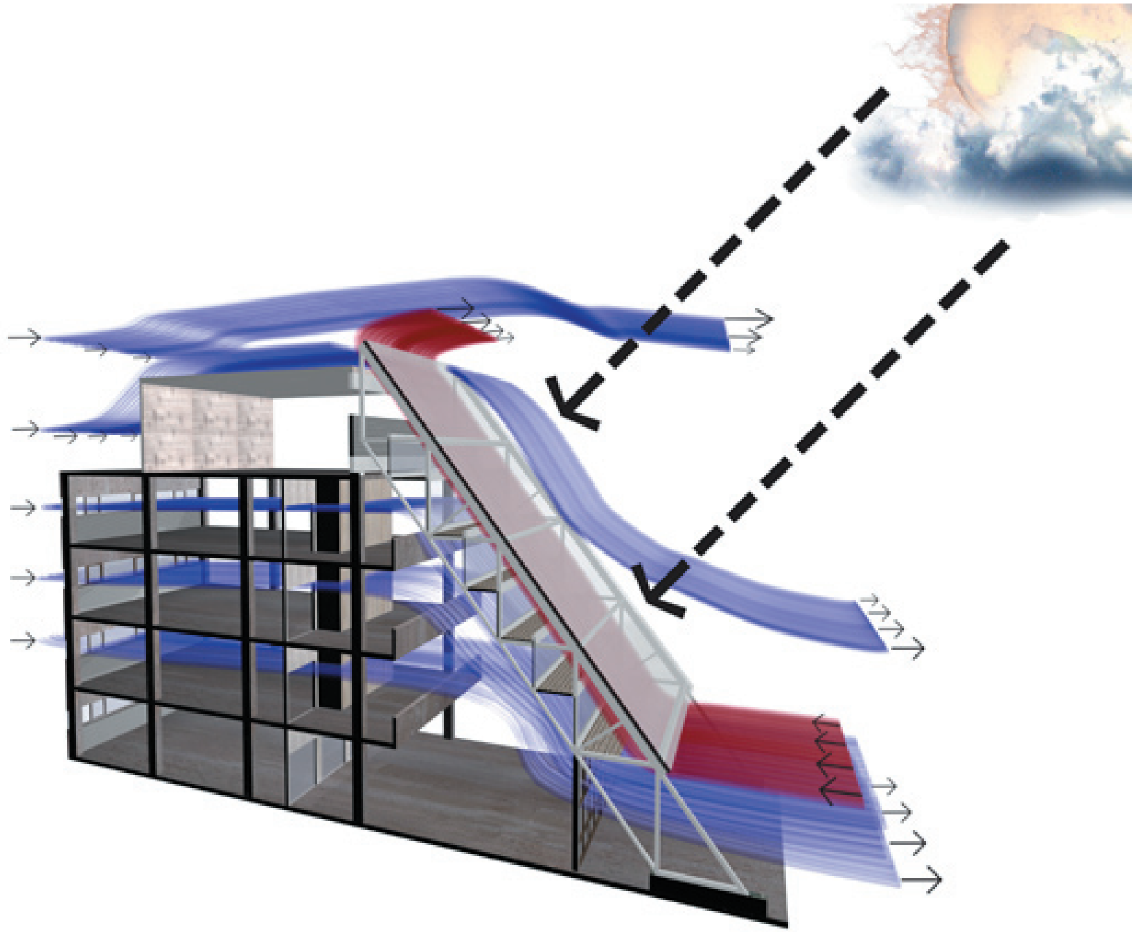
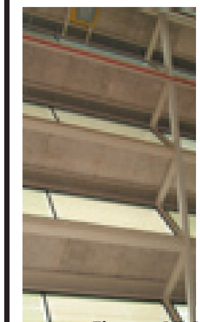


Figure 17.A. Natural Ventilation scheme B.
(Diagram by Steven R. Cook, 2003)



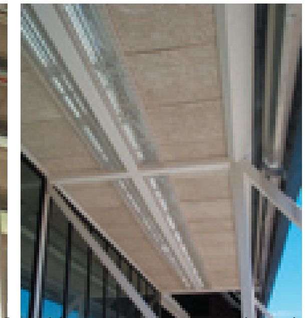


Figure 17.1. Atrium dampers are closed.
(Photo by Steven R. Cook, 2003)

Figure 17.2. Top and bottom louvers are open.
(Photo by Steven R. Cook, 2003)

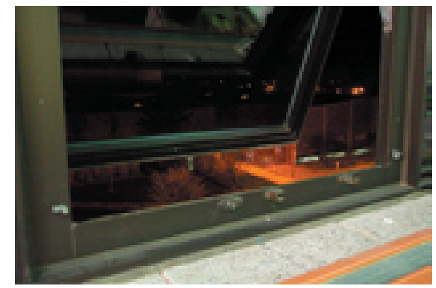


Figure 17.3. Operable windows on the north facade are open.
(Photo by Steven R. Cook, 2003)

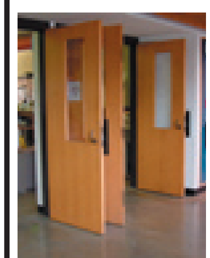


Figure 17.4. Studio doors are open.
(Photo by Steven R. Cook, 2003)

Figure 17.5. Atrium doors are open.
(Photo by Steven R. Cook, 2003)

CASE F:

Typical Weather Conditions		Intended Operational Procedure
Temp.	48 - 80 degrees (Fahrenheit)	Open North Windows
Wind spd.	10.3 MPH (north)	Open South Doors
NO. Days	42 days/Year	Open Lower Vent
		Close Unit Dampers

The north wind creates negative air pressure and pulls air through the building. A stack effect is still created inside the solar chimney from the sun and is able to draw air in a reverse direction. This scheme can no longer work due to the operable windows being bolted shut, the studio doors being locked for security reasons, and the south atrium doors remaining in the closed position.

Test 1 Schedule

Test began at 12:00 pm on Wednesday April 9

Test completed at 12:05 pm on Friday April 11

Figure 18.1. Blinds are in the "filtered" position (horizontal).
(Photo by Robert J. Patton, 2003)

Figure 18.2. Top and bottom louvers are "closed."
(Photo by Steven R. Cook, 2003)

In order to establish operating guidelines for the new schemes, a series of experiments will be conducted on the CAP solar chimney. The collected data will help establish an understanding of the temperature ranges by which to set the controls for the operation of the solar chimney throughout the year.

The first testing protocol for the solar chimney has the top and bottom air louvers closed and the solar dampers at a "filtered" position. It is expected that the temperature sensors inside the solar chimney will highly differ from the outdoor air temperature because the closed system will allow the trapped volume of air to be heated by the sun (some variance will occur among the sensors inside the solar chimney due to an interior stack effect). The "filtered" solar damper position blocks some light and allows some to pass through the glass into the building. With this position of the solar dampers, solar heat gain should occur both inside the solar chimney and inside the CAP atrium, resulting in a higher temperature inside the solar chimney than if the blinds were in the "open" position.

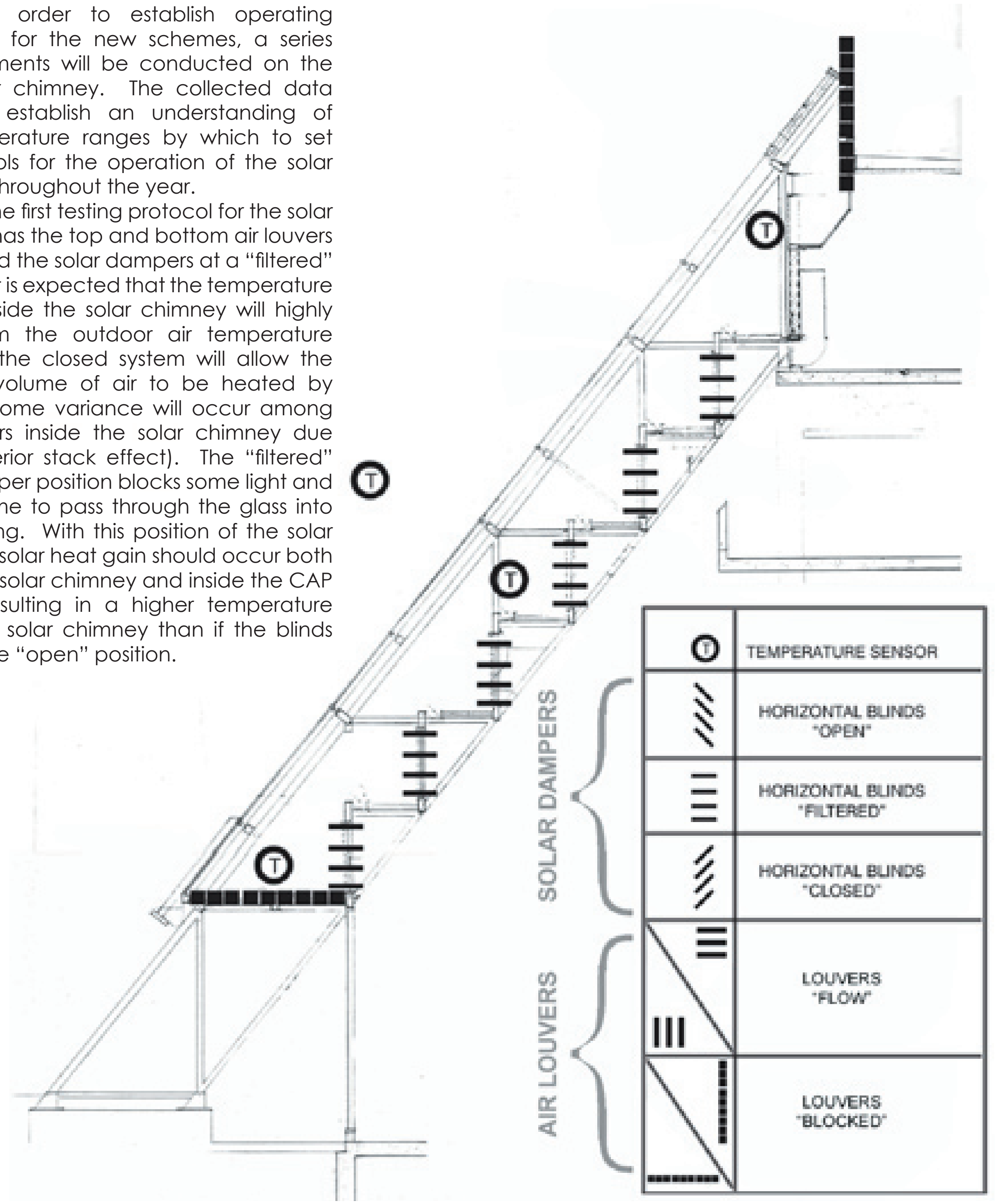


Figure 18.A. Test 1: Sunlight Filtered/Air Blocked.

The second testing protocol for the solar chimney has the top and bottom air louvers open and the solar dampers at a "filtered" position. It is expected that the temperature sensors inside the solar chimney will have little variance among each other because the air louvers will be open allowing the outside air to constantly flush through the solar chimney. The "filtered" solar damper position blocks some light and allows some to pass through the glass. With this position of the solar dampers, solar heat gain should occur both inside the solar chimney and inside the CAP atrium. The "open" position of the solar chimney will exhaust any heat gains that occur inside the chimney.

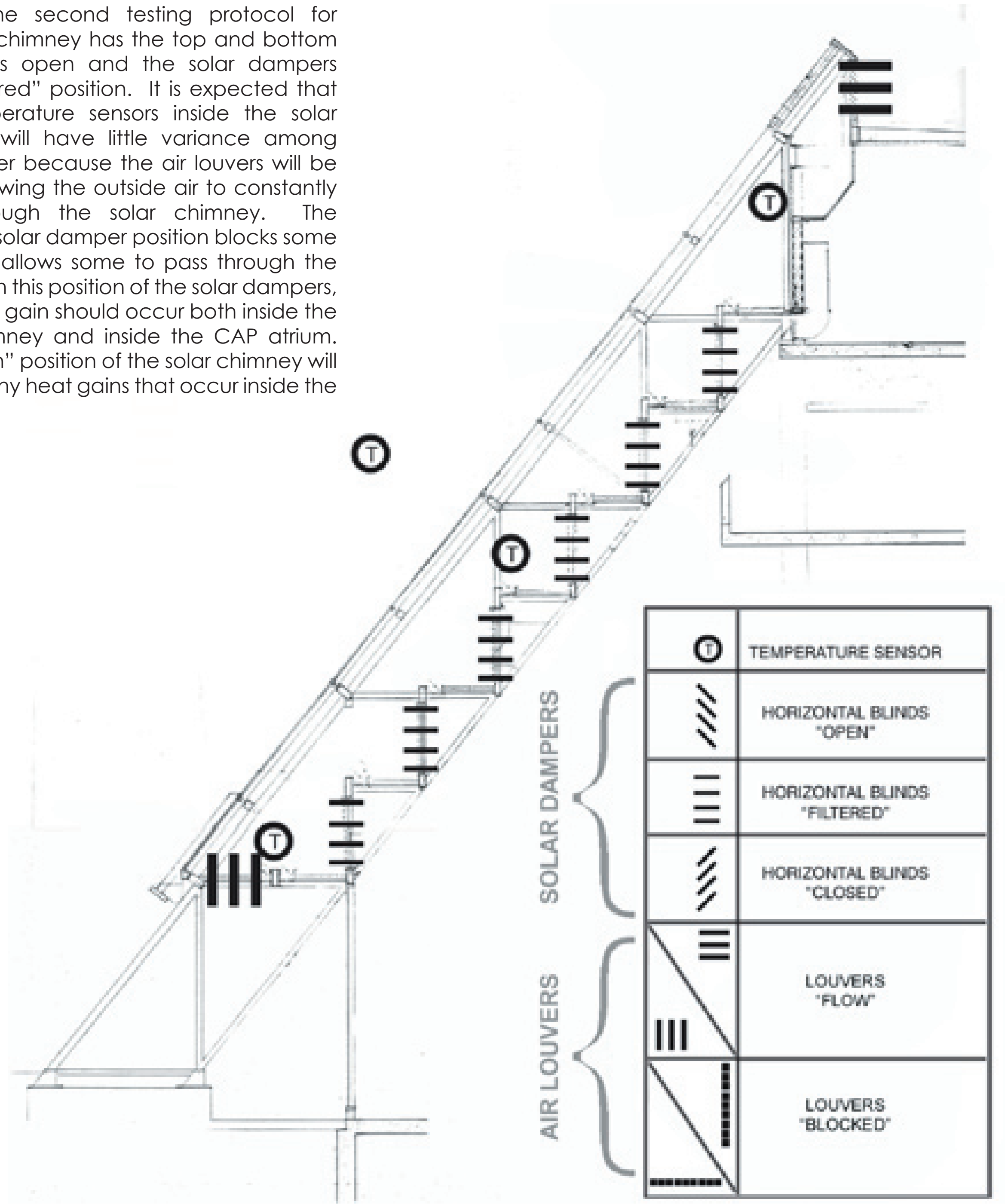


Figure 19.A. Test 2: Sunlight Filtered/Air Flow.

Test 2 Schedule

Test began at 12:05 pm on Friday April 11

Test completed at 12:05 pm on Sunday April 13

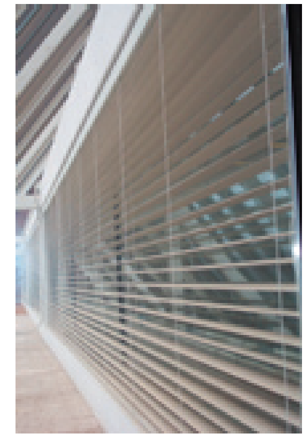


Figure 19.1. Blinds are in the "filtered" position (horizontal).
(Photo by Robert J. Patton, 2003)

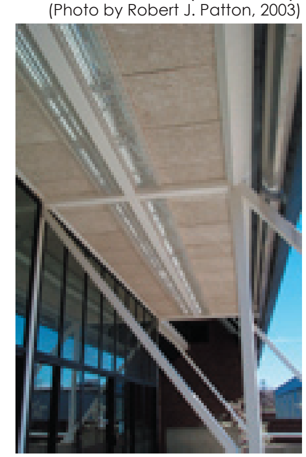


Figure 19.2. Top and bottom louvers are "open."
(Photo by Steven R. Cook, 2003)

Test 3 Schedule

Test began at 12:05 pm on Sunday April 13

Test completed at 12:05 pm on Tuesday April 15

Figure 20.1. Blinds are in the "open" position.
(Photo by Robert J. Patton, 2003)

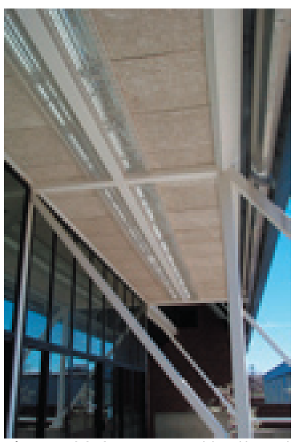


Figure 20.2. Top and bottom louvers are "open."
(Photo by Steven R. Cook, 2003)

The third testing protocol for the solar chimney has the top and bottom air louvers open and the solar dampers at an "open" position. It is expected that the temperature sensors inside the solar chimney will have little variance among each other because the air louvers will allow the outside air to constantly flush through the solar chimney. The "open" solar damper position will allow all the solar radiation to pass through the glass into the building; solar heat gain should occur primarily inside the CAP atrium.

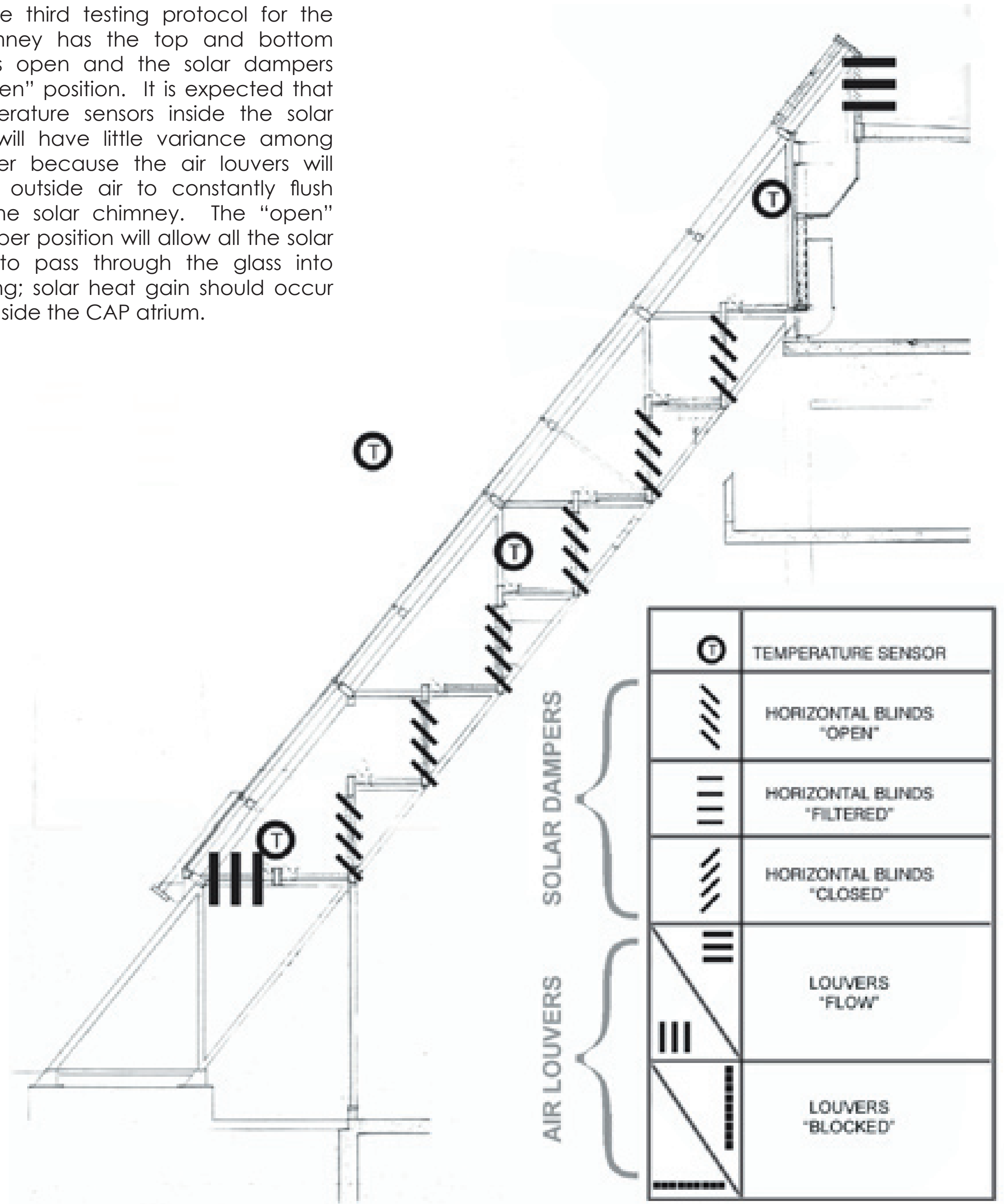


Figure 20.A. Test 3: Sunlight Open/Air Flow.

The fourth testing protocol for the solar chimney has the top and bottom air louvers closed and the solar dampers at a "open" position. It is expected that the temperature sensors inside the solar chimney will differ significantly from the outdoor air temperature because the closed system will allow the trapped volume of air to be heated by the sun (some variance will occur among the sensors inside the solar chimney due to an interior stack effect). The "open" solar damper position allows all solar radiation to pass through the glass. With this position of the solar dampers, solar heat gain should only occur inside the CAP atrium, resulting in a higher temperature inside the solar chimney, but not as high as if the solar dampers were in the "closed" position.

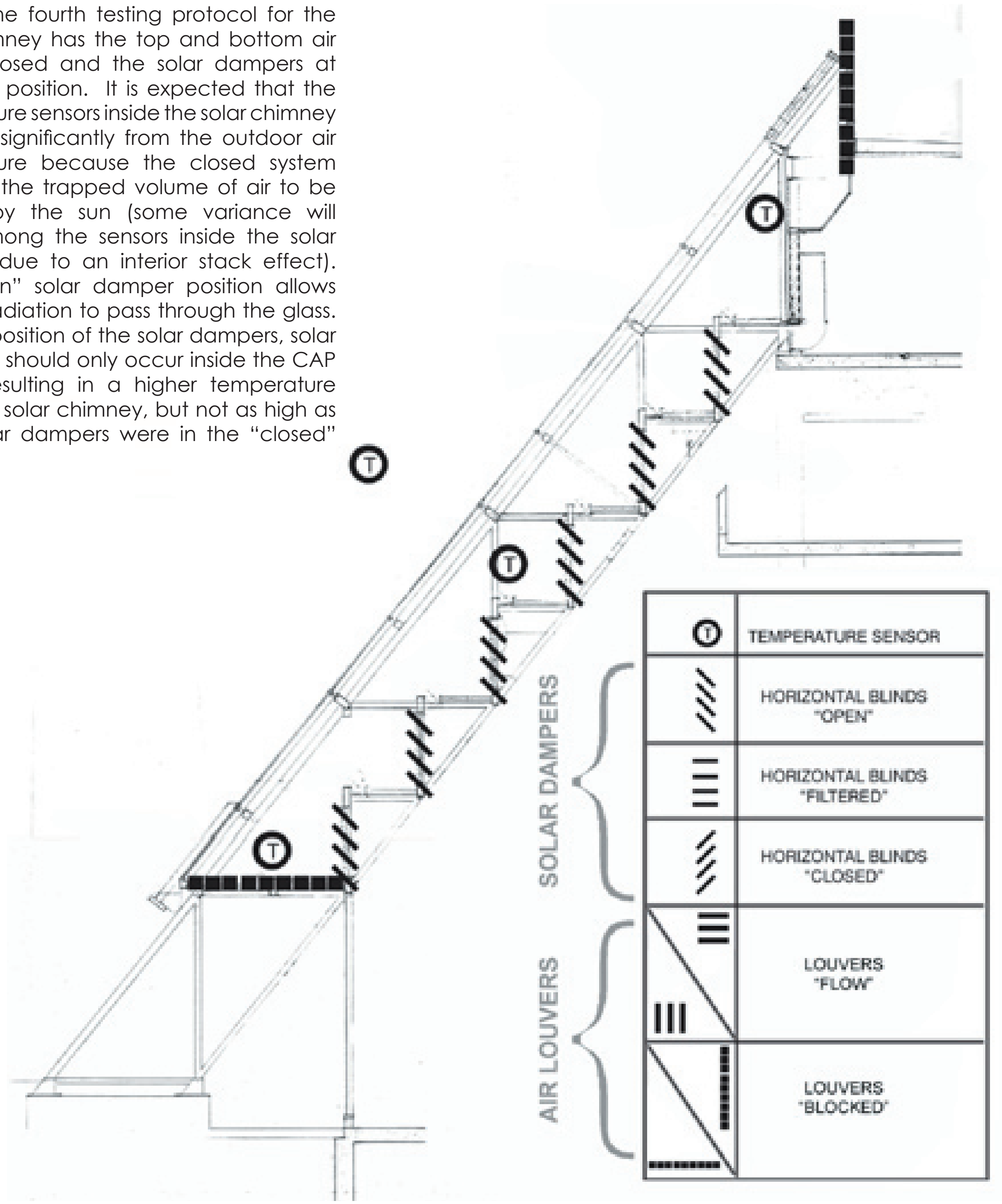


Figure 21.A. Test 4: Sunlight Open/Air Blocked.

Test 4 Schedule

Test began at 12:05 pm on
Tuesday April 15

Test completed at 12:05 pm on
Thursday April 17

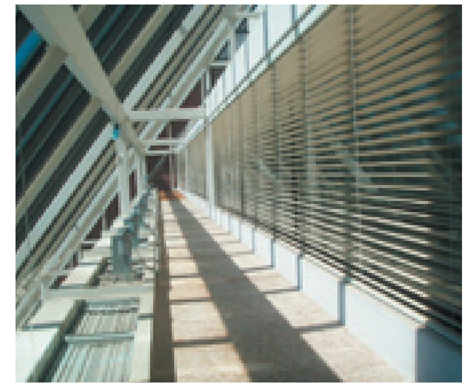


Figure 21.1. Blinds are in the "open" position.
(Photo by Robert J. Patton, 2003)

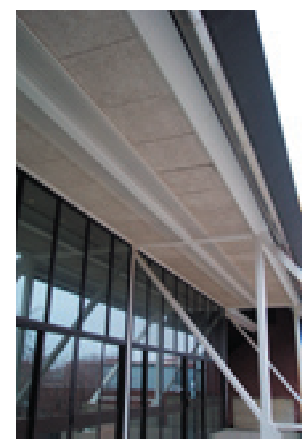


Figure 21.2. Top and bottom louvers are "closed."
(Photo by Steven R. Cook, 2003)

Test 5 Schedule

Test began at 12:05 pm on Thursday April 17

Test completed at 12:05 pm on Saturday April 19

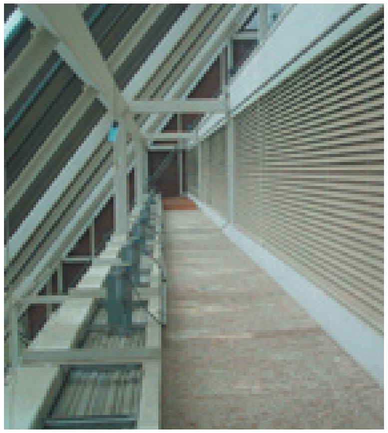


Figure 22.1. Blinds are in the "closed" position.
(Photo by Robert J. Patton, 2003)

Figure 22.2. Top and bottom louvers are "closed."
(Photo by Steven R. Cook, 2003)

The fifth testing protocol for the solar chimney has the top and bottom air louvers closed and the solar dampers at a "closed" position. It is expected that the temperature sensors inside the solar chimney will differ highly from the outdoor air temperature because the closed system will allow the trapped volume of air to be heated by the sun (some variance will occur among the sensors inside the solar chimney due to an interior stack effect). The "closed" solar damper position allows no solar radiation to pass through the glass into the building. With this position of the solar dampers, solar heat gain should occur primarily inside the solar chimney, resulting in the highest temperature of all of the tests.

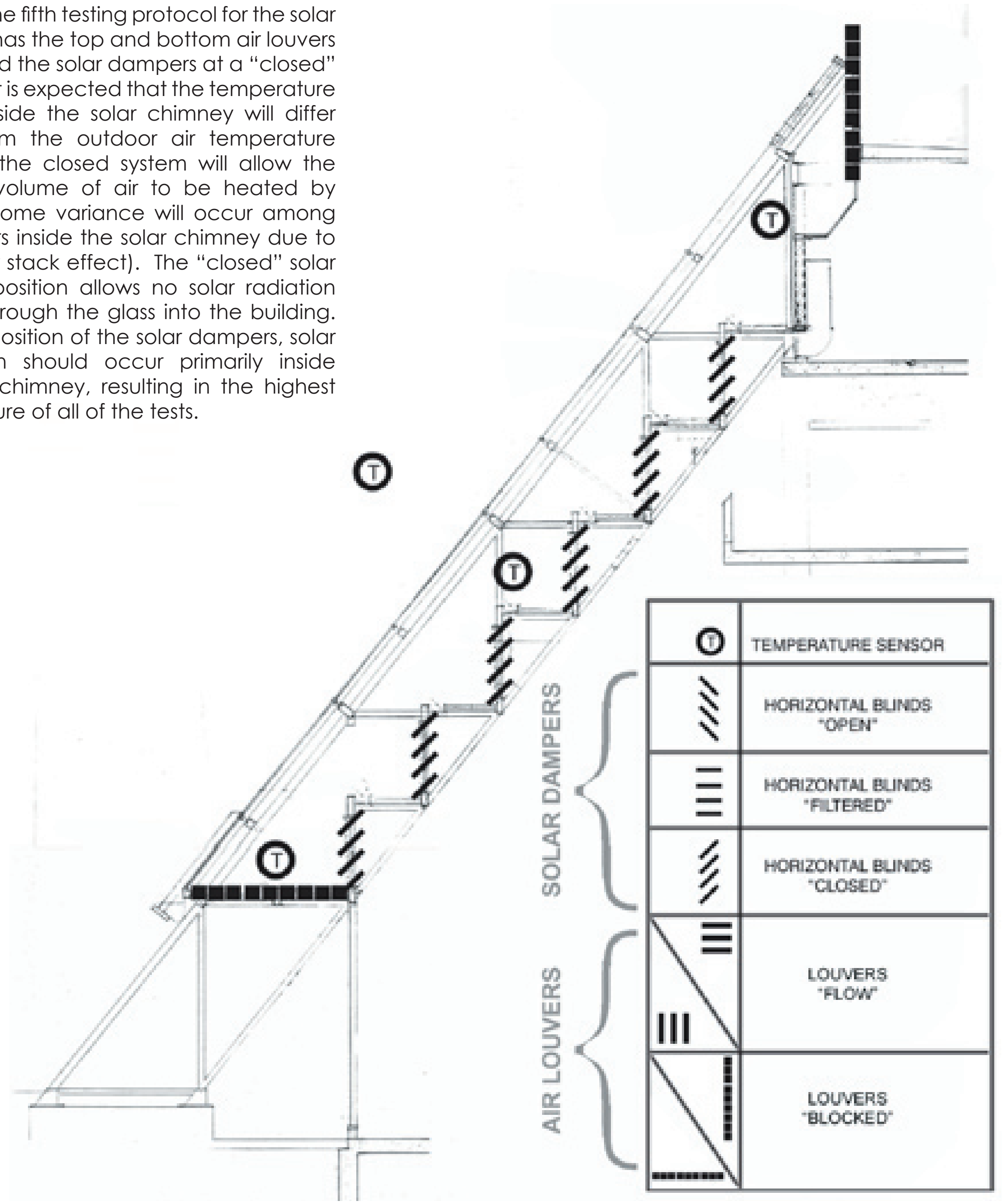


Figure 22.A. Test 5: Sunlight Closed/Air Blocked.

The sixth testing protocol for the solar chimney has the top and bottom air louvers open and the solar dampers at a "closed" position. It is expected that the temperature sensors inside the solar chimney will have little variance among each other because the air louvers will be open allowing the outside air to constantly flush through the solar chimney. The "closed" solar dampers position allows no solar radiation to pass through the glass. With this position of the solar dampers, solar heat gain should only occur inside the solar chimney, yielding no temperature change, but exhausting the most amount of heat gains.

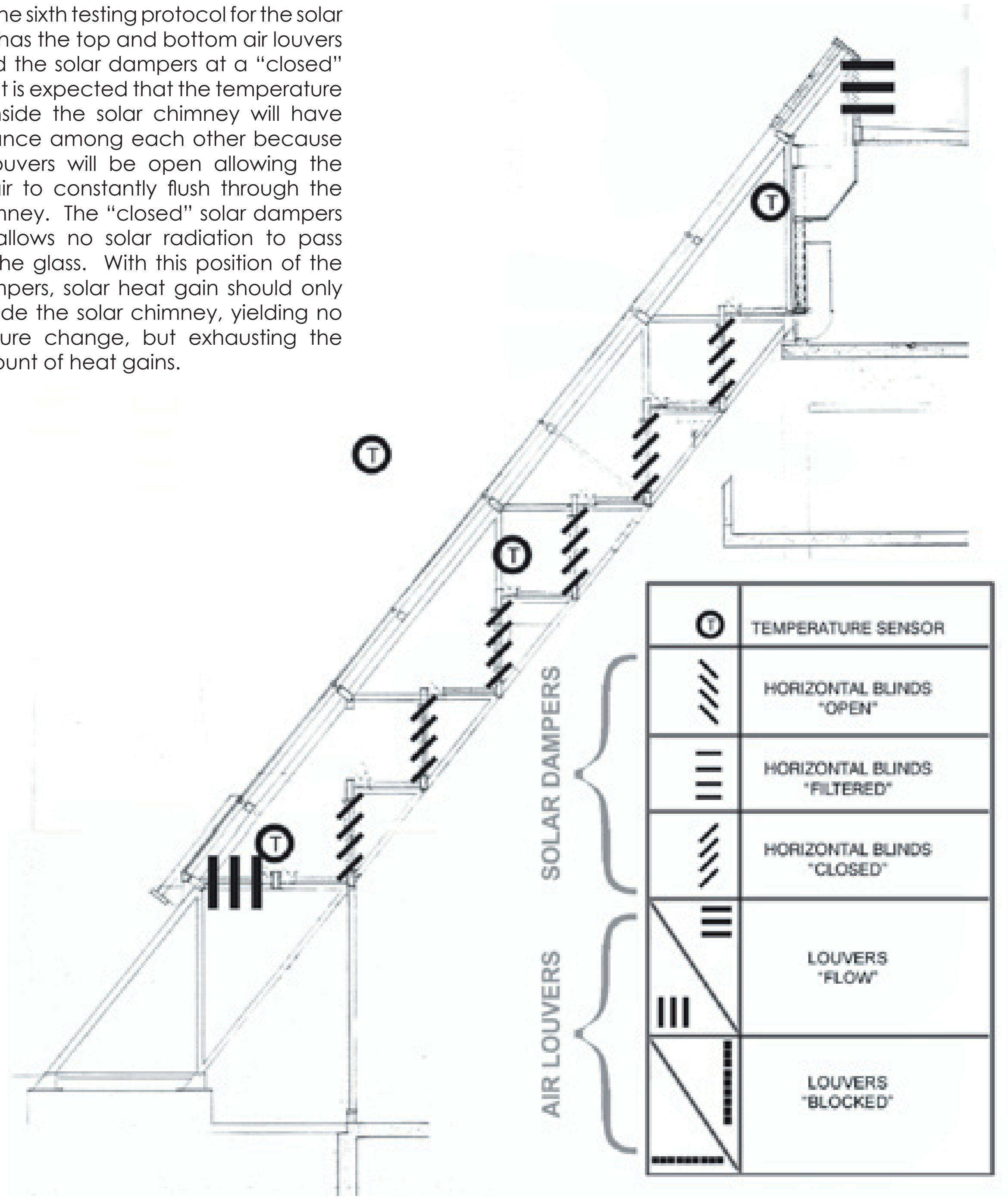


Figure 23.A. Test 6: Sunlight Closed/Air Flow.

Test 6 Schedule

Test began at 12:05 pm on Saturday April 19

Test completed at 12:05 pm on Monday April 21

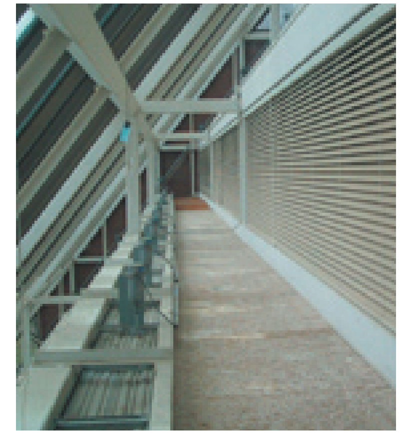


Figure 23.1. Blinds are in the "closed" position.
(Photo by Robert J. Patton, 2003)

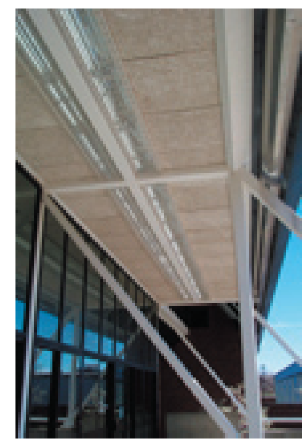


Figure 23.2. Top and bottom louvers are "open."
(Photo by Steven R. Cook, 2003)

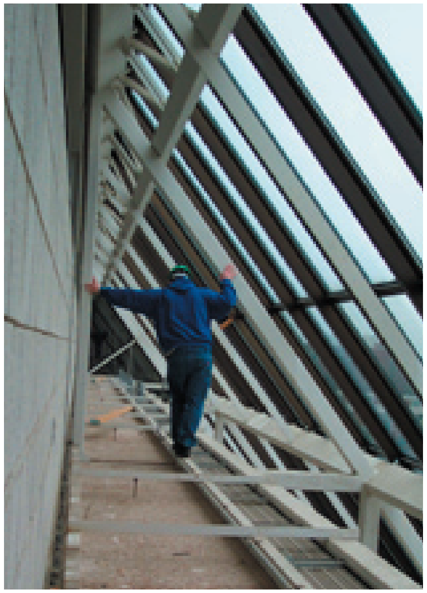


Figure 24.1. Balancing on the walkable area to place the temperature recording devices inside the CAP solar chimney.
(Photo by Robert J. Patton, 2003)

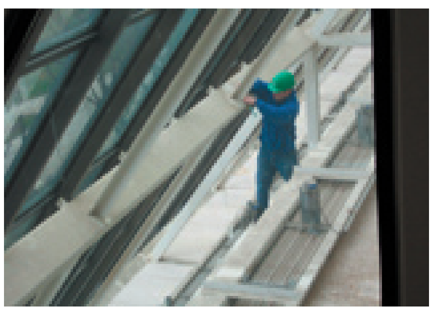


Figure 24.2. Placing the StowAway temperature recording instruments inside the CAP solar chimney.
(Photo by Robert J. Patton, 2003)

CLIMATIC DATA (4/9-4/21)

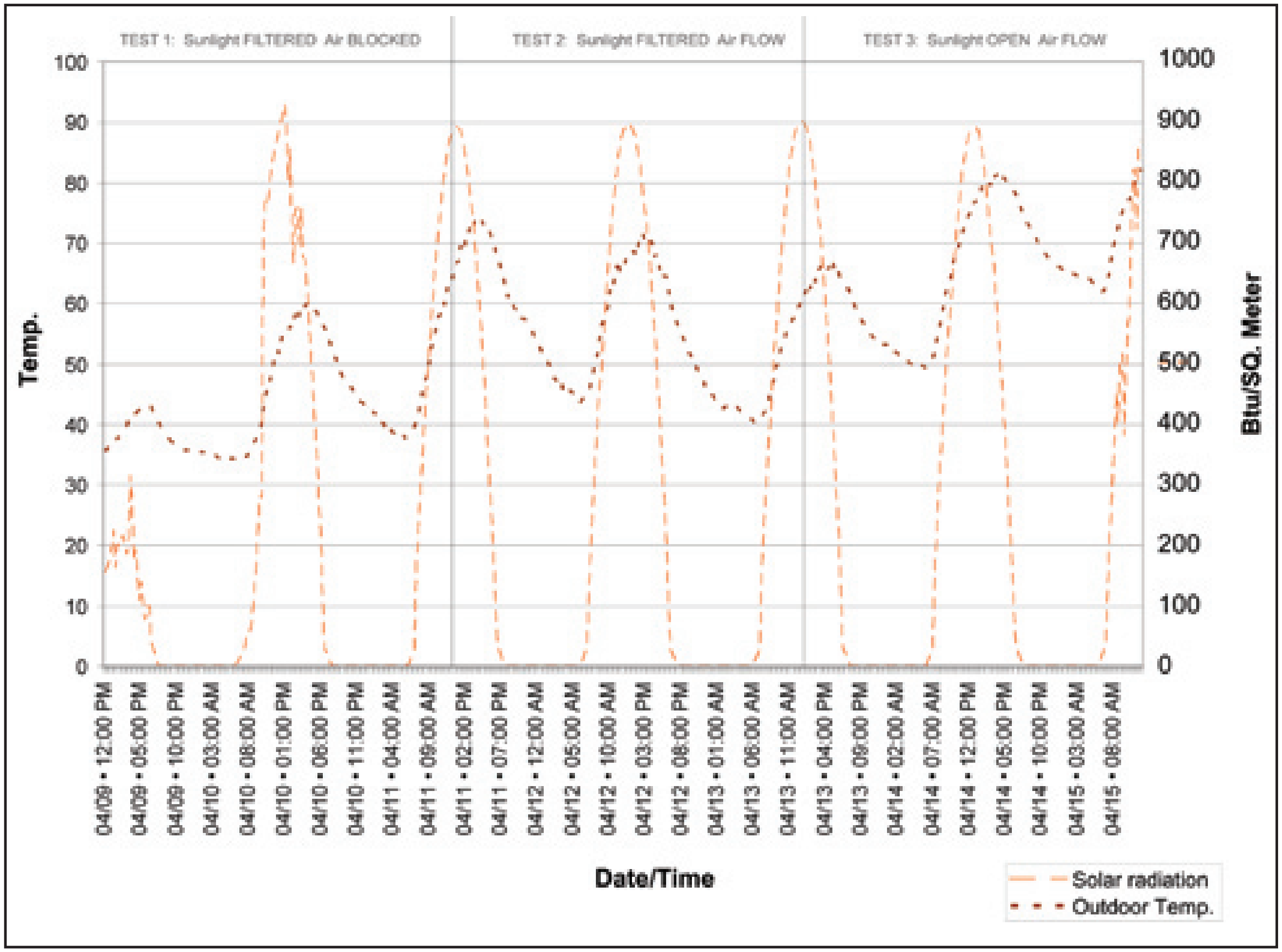


Figure 24.A. Outdoor air temperature and solar radiation graph.

NOTE: All temperatures are recorded and displayed in degrees Fahrenheit.

CLIMATIC DATA (4/9-4/21) CONT.

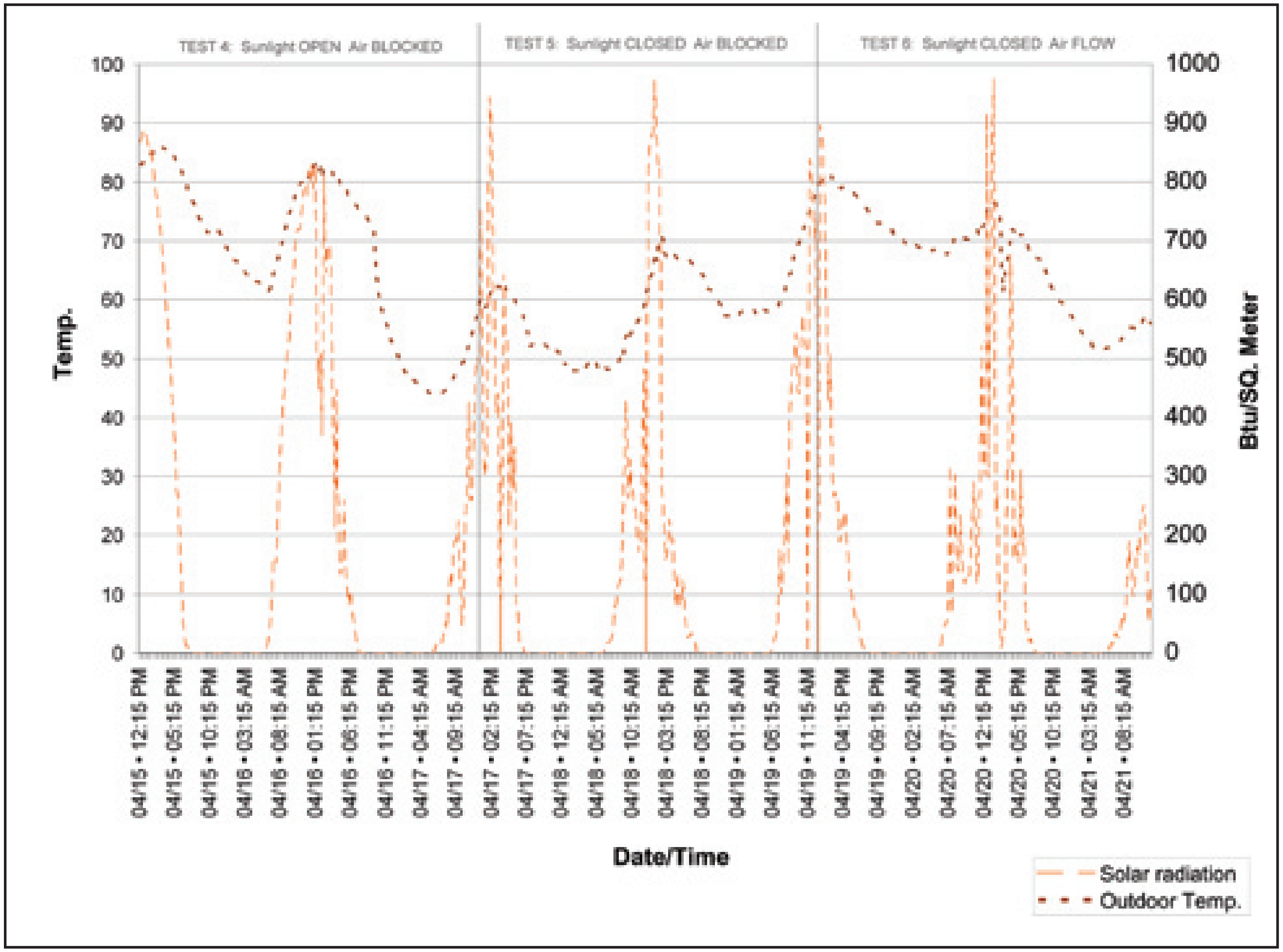


Figure 25.A. Outdoor air temperature and solar radiation graph (cont.).

The outdoor air temperature and solar radiation graph illustrates the weather conditions that took place during the testing period. Throughout the two weeks, the average daily temperature readings generally remained within a 25 degree range (51-76 degrees). The average daily high temperature during the testing period was 76.4 degrees while the average daily low temperature was 51.8 degrees, resulting in an overall average temperature of 64.1 degrees. The solar radiation data represents the intensity of sunlight throughout each day. The average daily solar radiation intensity was 878.7 BTU/M^2. Although this average represents a high level of solar radiation, the graph illustrates the fluctuation of sunny and cloudy days. Days with full sun produce a regular pattern as represented in the first three testing periods (Figure 24.A.). Cloud cover impacts the graph with irregular variations such as those occurring during the last three testing periods (Figure 25.A.).

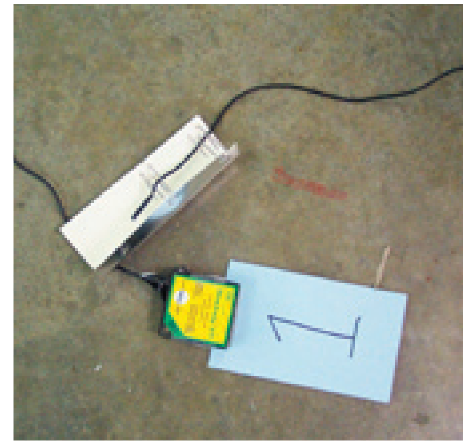


Figure 25.1. StowAway temperature recording device w/wire sensor, sun shield, and label.
(Photo by Robert J. Patton, 2003)

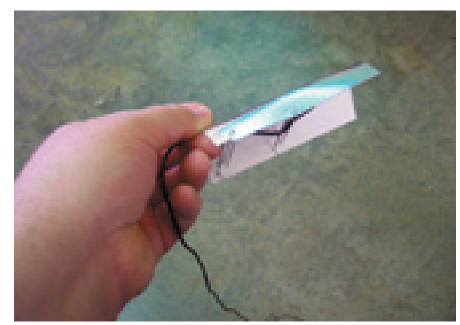


Figure 25.2. Detail of sun shield and wire sensor.
(Photo by Robert J. Patton, 2003)

Figure 26.1. Louver control panel.
(Photo by Robert J. Patton, 2003)

Figure 26.2. Dave Bartle changing the louver settings for Test 2.
(Photo by Robert J. Patton, 2003)

OVERALL TEMPERATURE DATA

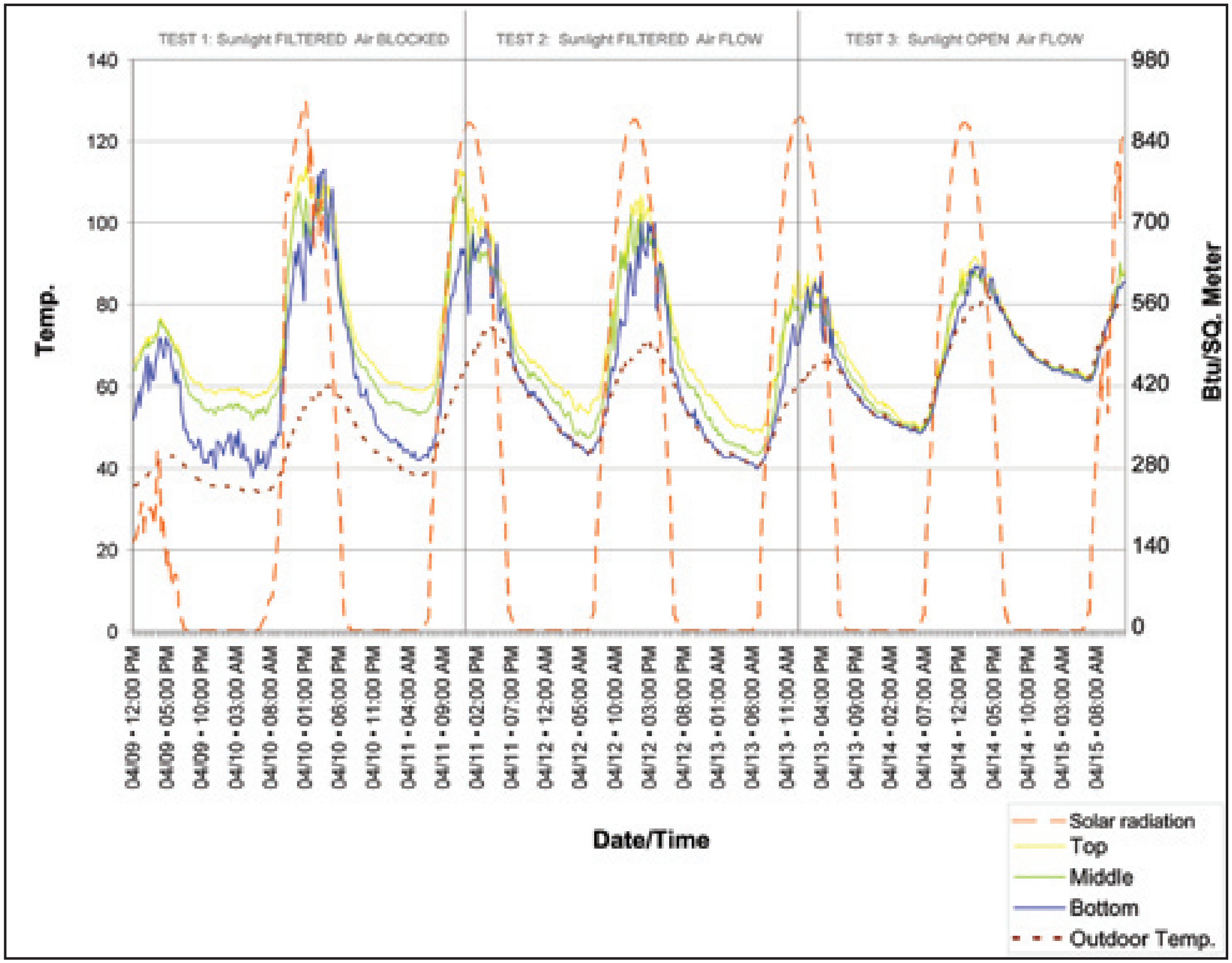


Figure 26.A. Overall solar chimney temperature graph.

NOTE: After the placement of the StowAway sensors within the cavity of the solar chimney, the shading shield of the bottom sensor became exposed to direct sunlight. Due to this circumstance, the bottom temperature recordings may not remain relative to the other recordings during times of full sun.

OVERALL TEMPERATURE DATA (CONT)

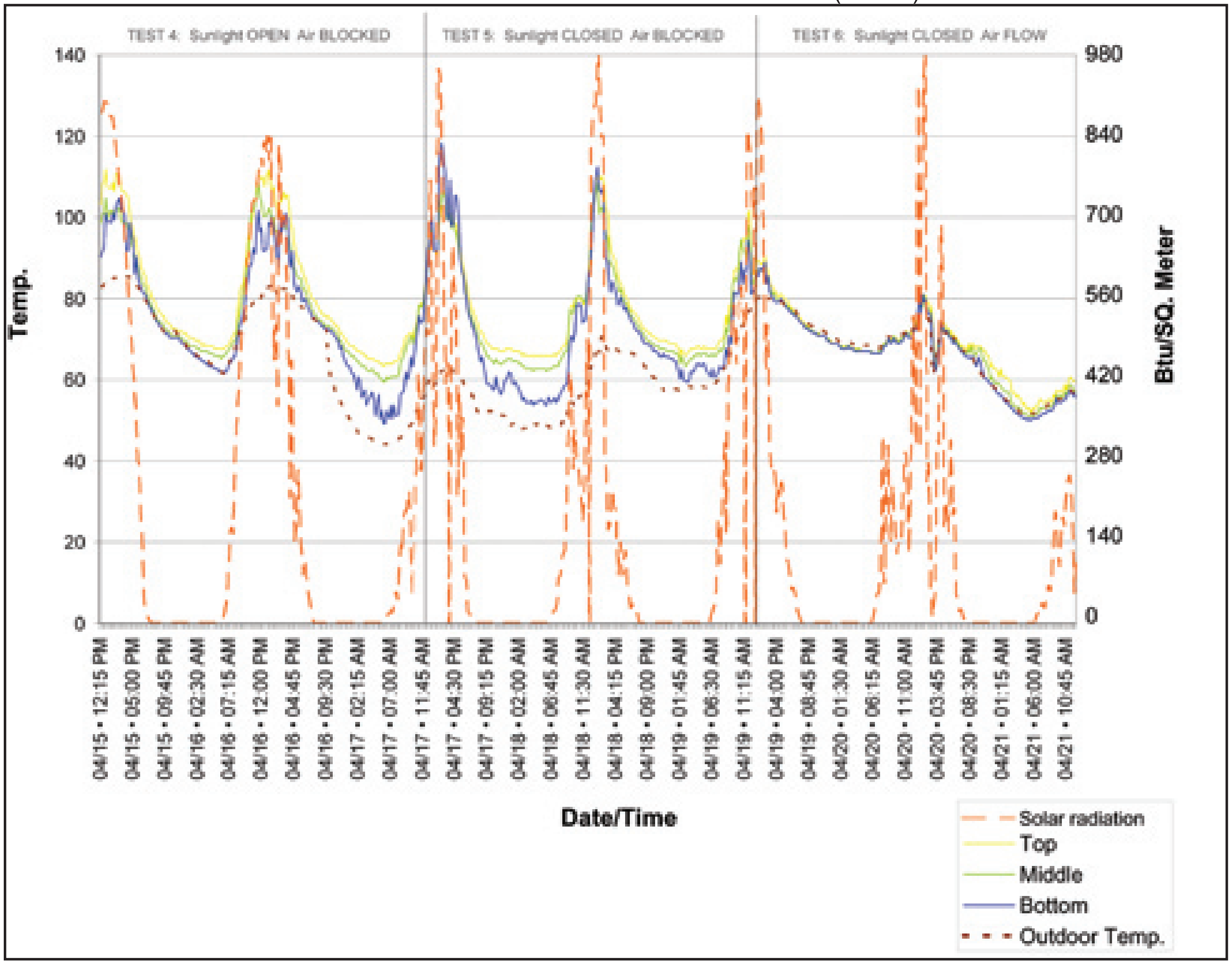


Figure 27.A. Overall solar chimney temperature graph (cont.).

The combined temperature and solar radiation graph compares the outdoor climatic conditions with the temperatures that were taken inside the solar chimney. The graph illustrates the wide variety of responses that occur when alterations are made to the operating scheme of the solar chimney. These responses are influenced by the natural forces of air temperature and intensity of solar radiation. The solar chimney's performance is represented by three temperature readings taken within the cavity of the solar chimney. The three temperature readings were recorded at the top, middle, and bottom of the solar chimney. The graph illustrates the variety of responses that occur due to varying levels of solar radiation during the different testing protocols. For example, when the graph of the first testing protocol is compared with the third testing protocol (Figure 26.A.), a large temperature difference is seen between the outdoor air temperature and the temperature inside the solar chimney.

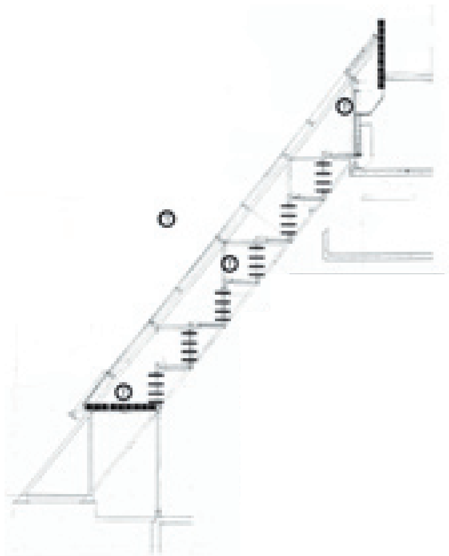


Figure 28.1. Blinds are in the "closed" position.
(Diagram by Steve Cook, 2003)

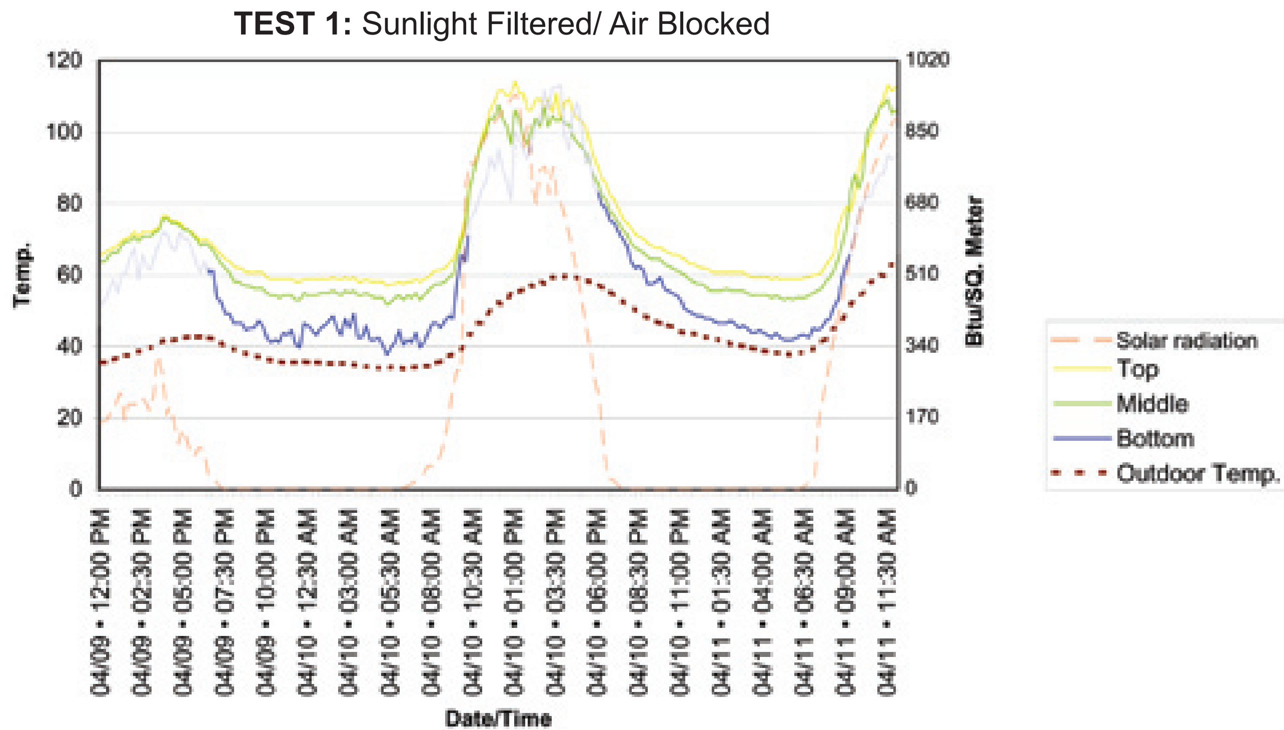


Figure 28.A. Test 1: Sunlight Filtered/Air Blocked graph.

Test one was performed with the top and bottom air louvers "blocked" position and with the solar blinds in the "filtered" position. The resulting graph illustrates the significant temperature difference between the air in the solar chimney cavity and the outdoor air; the outside temperature reaches close to 60 degrees and the air temperature inside the solar chimney peaks above 110 degrees (Figure 28.A.). The three temperature sensors recorded temperatures at the top, middle, and bottom of the solar chimney cavity. In this operating scheme, the sensors varied as much as 10 degrees between the readings of the top and bottom temperatures. This variance in temperature occurs throughout the entire testing period, which verifies internal stratification of air temperature within the solar chimney throughout the day and night. The temperature recordings suggest that the temperatures within the solar chimney closely respond to the increase of solar radiation during the beginning of daylight hours. As the solar radiation drops at the end of daylight hours, however, the air temperature inside the solar chimney does not lose its solar heat energy for some time, resulting in a time-lag effect.

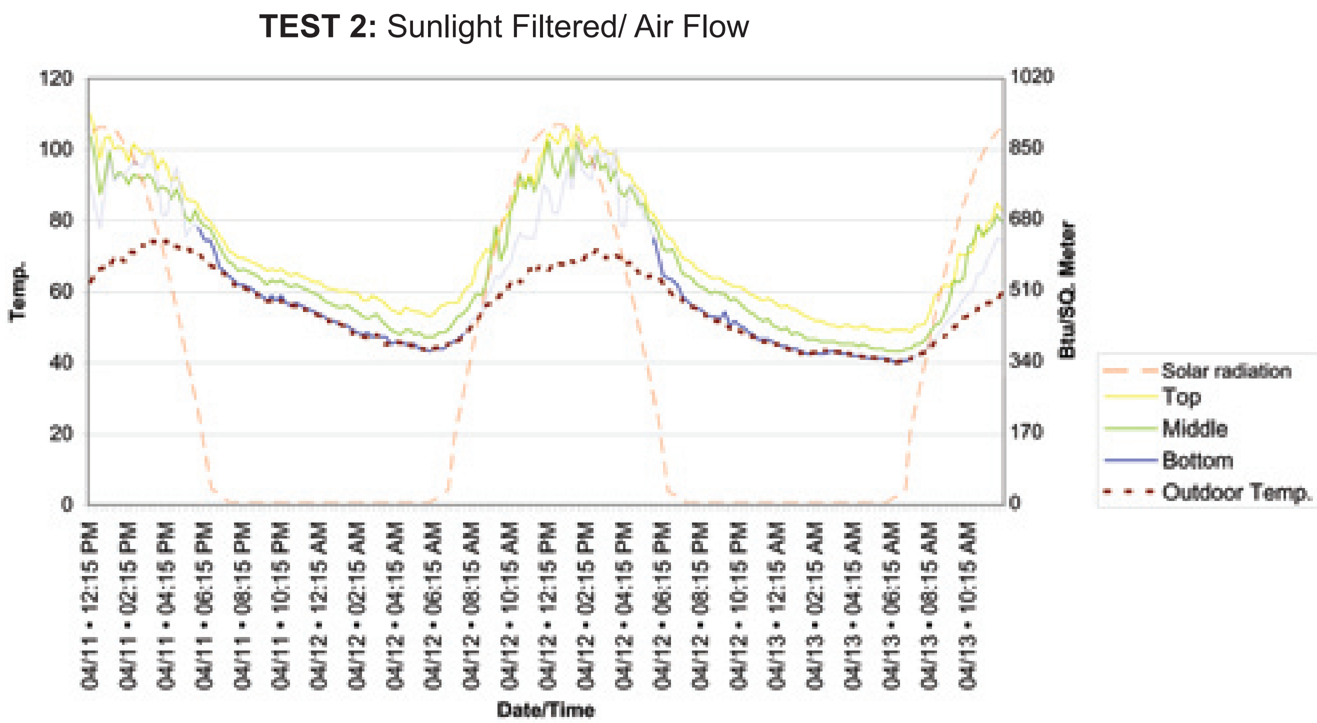


Figure 29.A. Test 2: Sunlight Filtered/Air Flow graph.

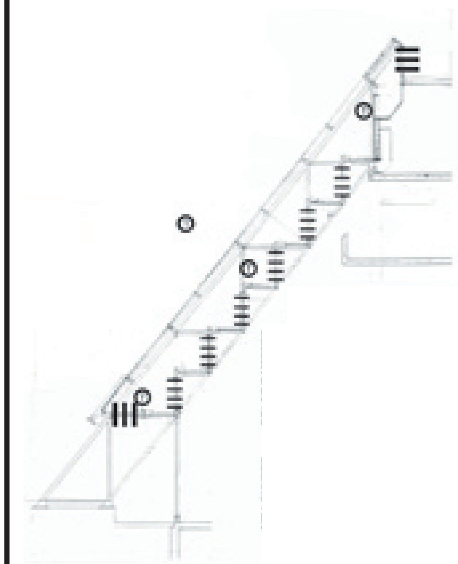


Figure 29.1. Blinds are in the "closed" position.
(Diagram by Steve Cook, 2003)

Test two was performed with the top and bottom air louvers in the "flow" position and with the solar blinds in the "filtered" position. By opening the air flow louvers of the solar chimney, air is drawn into, up through, and out the top of the chimney. During the daylight hours, the stratification between the outdoor air temperature and the temperature inside the solar chimney is much less, compared to the stratification of the "blocked air" position. The temperature recordings within the solar chimney follow more closely with the rise and fall of solar radiation values resulting in slower temperature time-lag. During the nighttime hours the bottom sensor recorded temperatures that follow almost exactly with the outdoor temperature.

The stratification during both tested nighttime periods are consistent with each other, demonstrating the existence of a stack effect caused by the rising of warm air through the solar chimney.

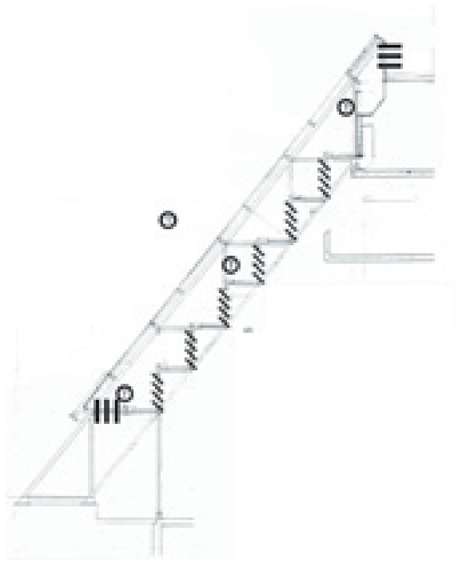


Figure 30.1. Blinds are in the "closed" position.
(Diagram by Steve Cook, 2003)

TEST 3: Sunlight Open/ Air Flow

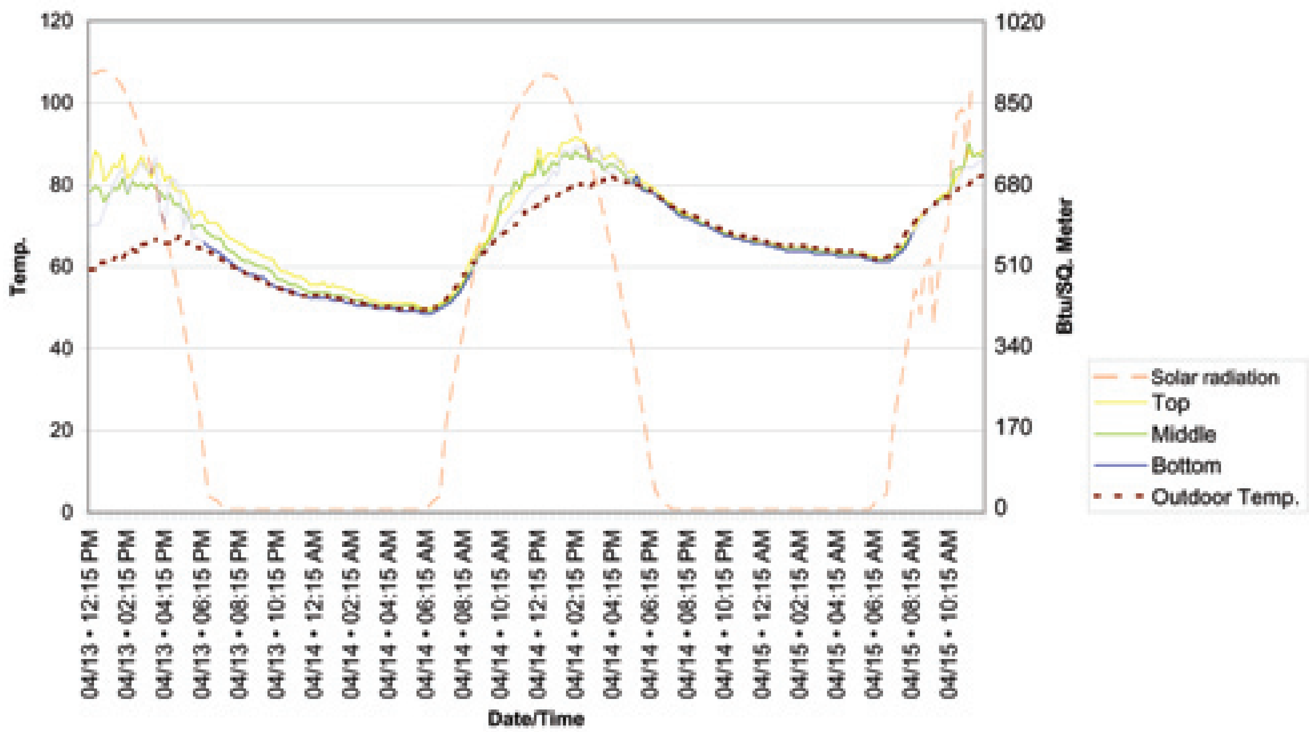


Figure 30.A. Test 3: Sunlight Open/Air Flow graph.

Test three was performed with the top and bottom air louvers in the "flow" position and with the solar blinds in the "open" position. By opening the solar chimney, air is drawn into, up through, and out the top of the chimney. During the daylight hours, the stratification between the outdoor air temperature and the temperature inside the solar chimney is minimal, remaining within a 10 degree difference. The temperature recordings within the solar chimney follow more closely with the rise and fall of the outdoor temperature values, however, this test indicates a reverse time-lag effect as temperatures decrease in the afternoon hours of the day. During the two nighttime durations, the stratification between the outdoor air temperature and the recorded temperature inside the solar chimney has a different behavior. The stratification of the air temperatures on the first night of this testing phase slowly contract to an almost equal temperature to that of the outdoor air temperature. The stratification of the air temperature on the second night quickly contracts to an almost equal temperature to that of the outdoor air temperature.

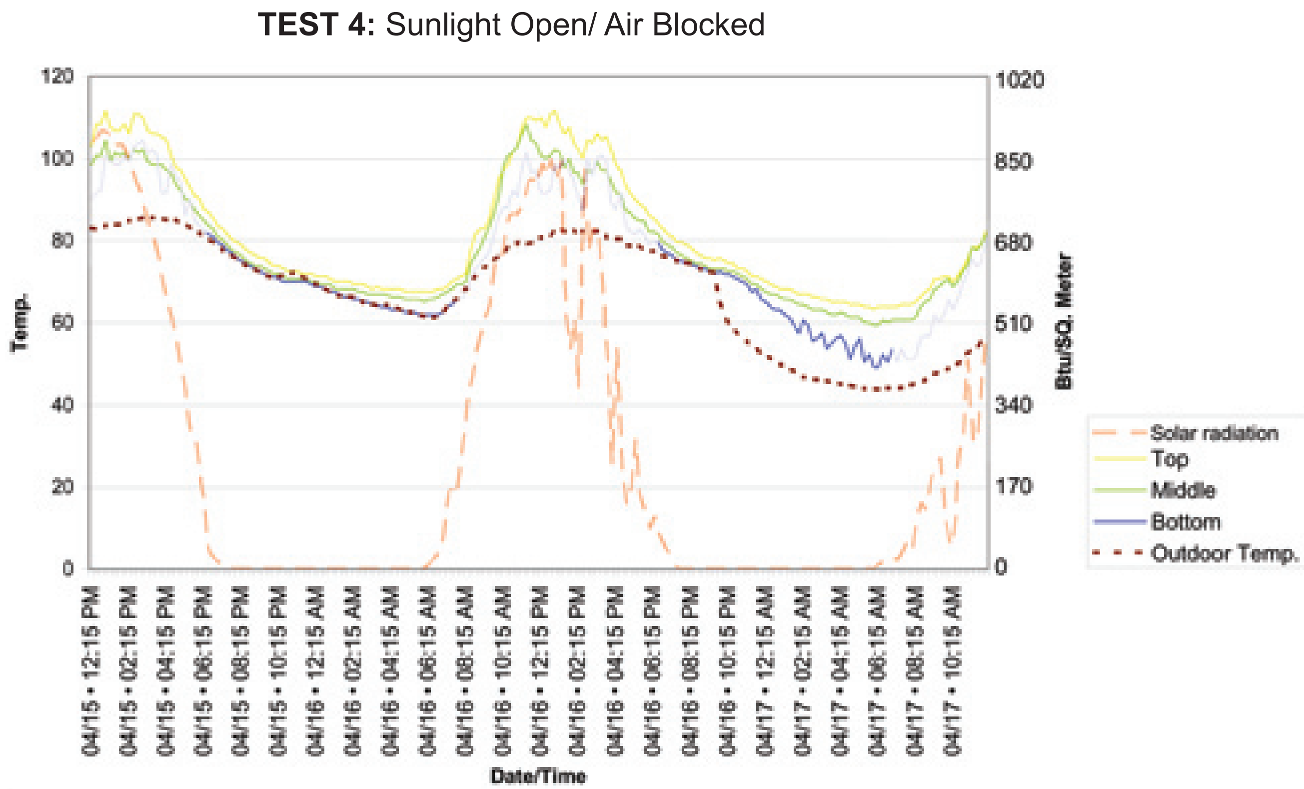


Figure 31.A. Test 4: Sunlight Open/Air Blocked graph.

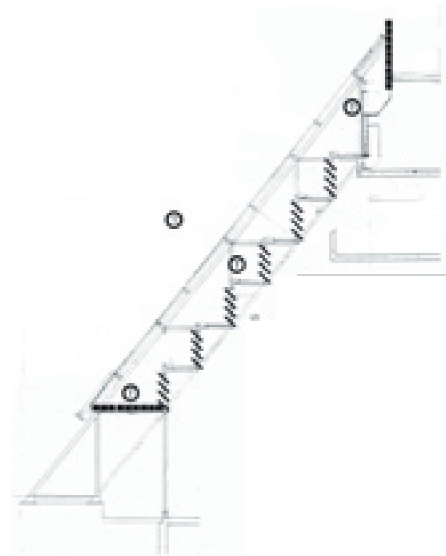


Figure 31.1. Blinds are in the "closed" position.
(Diagram by Steve Cook, 2003)

Test four was performed with the top and bottom air louvers in the "blocked" position and with the solar blinds in the "open" position. During the daylight hours, the stratification between the outdoor air temperature and the temperature inside the solar chimney is relatively low when compared to the stratification of test one (Figure 28.A.). The reason for the low level of stratification is a result of lower levels and inconsistent behavior of solar radiation. The temperature recordings within the solar chimney closely follow the outdoor air temperature's behavior. The second night of the test, a sudden drop in outdoor air temperature occurred, possibly due to a cold front. During this sudden temperature drop, the stratification between the outdoor air temperature and the temperatures within the solar chimney dramatically increased with a range of 20 degrees.

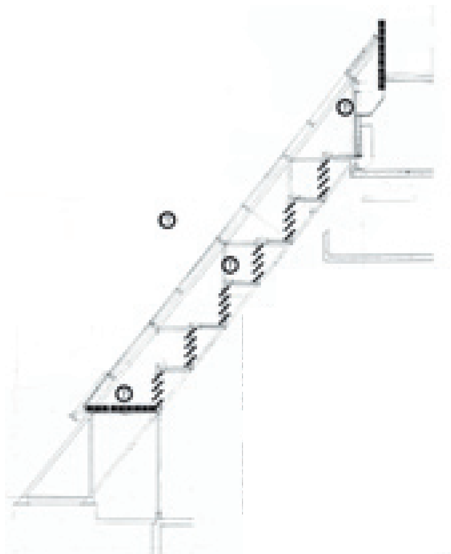


Figure 32.1. Blinds are in the "closed" position.

TEST 5: Sunlight Closed/ Air Blocked

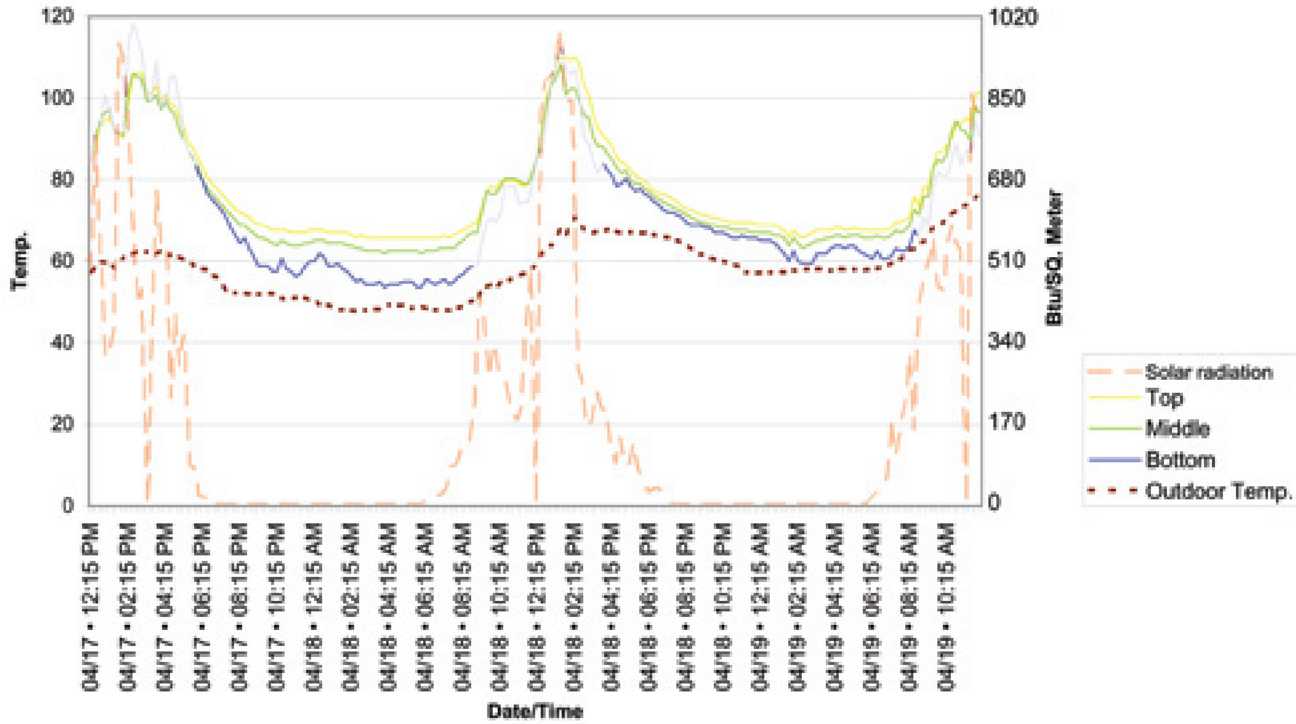


Figure 32.A. Test 5: Sunlight Closed/Air Blocked graph.

Test five was performed with the top and bottom air louvers in the "blocked" position and with the solar blinds in the "closed" position. By closing the top and bottom louvers of the solar chimney, air trapped within the cavity and can be charged with solar energy. The resulting graph illustrates the vast temperature difference between the air temperature inside of the solar chimney and the outdoor air temperature. The stratification during the daylight hours is relatively high when compared to the other open "air flow" schemes. The recorded outdoor air temperature and the temperatures inside the solar chimney ranged from about 70 degrees to about 110 degrees, resulting in a difference of over 40 degrees. The previous "blocked air" tests demonstrated a noticeable time-lag between the peaking of the outdoor air temperature and the temperature inside the solar chimney during the afternoon hours. In contrast to the previous "blocked air" tests, the solar radiation behavior during the test was inconsistent, which never allowed the trapped volume of air inside the solar chimney to store much solar heat energy.

TEST 6: Sunlight Closed Air Flow

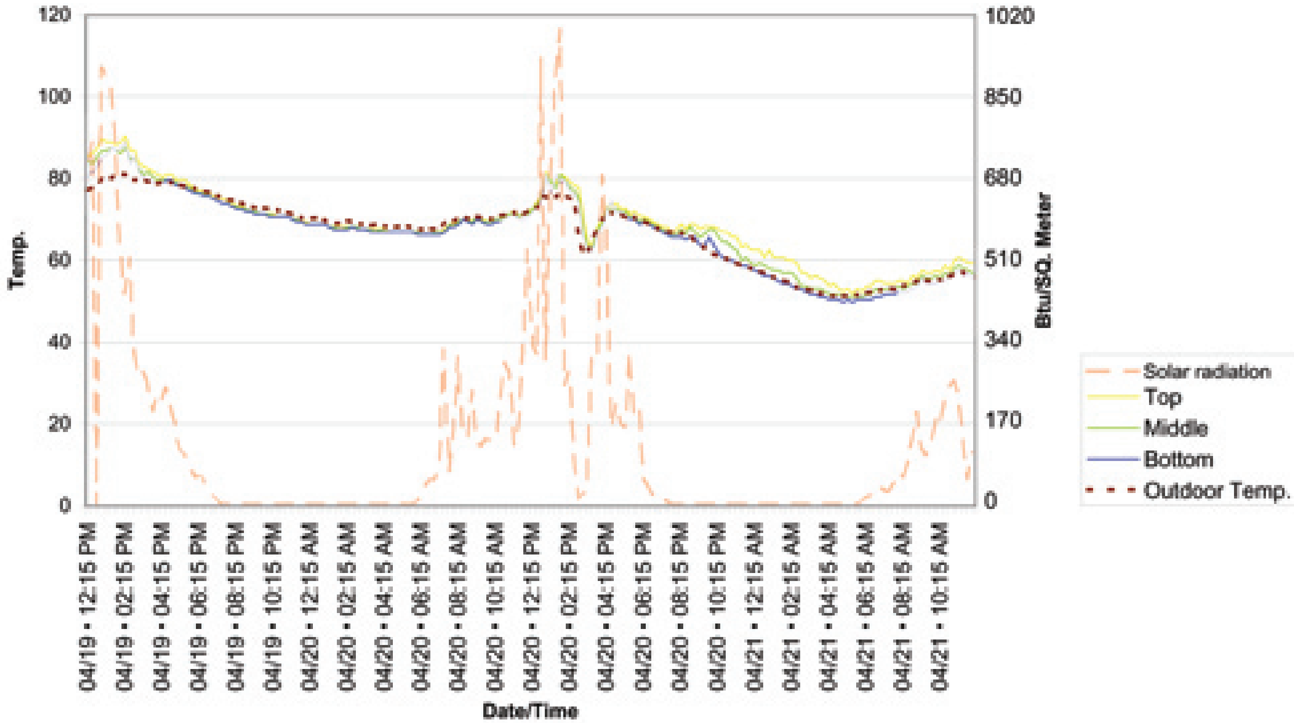


Figure 33.A. Test 6: Sunlight Closed/Air Flow graph.

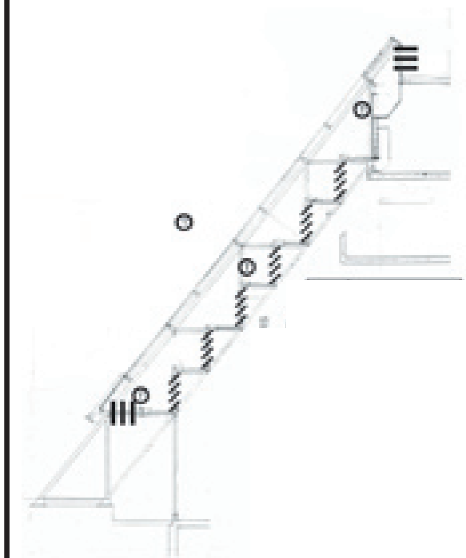


Figure 33.1. Blinds are in the "closed" position.

Test six was performed with the top and bottom air louvers in the "flow" position and with the solar blinds in the "closed" position. By opening the solar chimney, air is drawn into, up through, and out the top of the chimney. During the daylight and nighttime hours, the stratification between the outdoor air temperature and the temperature inside the solar chimney is extremely minimal, remaining within a 5 degree difference. The temperature recordings within the solar chimney follow more closely with the rise and fall of the outdoor temperature values, resulting in little, if any, time-lag in the temperature graphs. The lack of time-lag between outdoor air temperature and temperatures inside the solar chimney could be a result of the low levels and inconsistent behavior of solar radiation.

Comparing test 1- "Sunlight Filtered/Air Blocked" to test 3 - "Sunlight Open/Air Flow" reveals two different behaviors in the stratification of the temperatures within the solar chimney. As noted before, the stratification between the outdoor air temperature and the temperatures within the solar chimney vary greatly between the Air Blocked and Air Flow operating schemes. During the daylight hours of test 1 (Figure 34.A. & 34.1.), the stratification of the air temperatures between the top, middle, and bottom temperature sensor locations of the solar chimney increased relative to the increase of solar radiation. As the solar radiation value peaked, the solar chimney temperatures' stratification began to decrease, and eventually fall at the same rate as the solar radiation with a considerable amount of time lag. During the nighttime hours of test 1 (Figure 34.A. & 34.2.), the stratification of the air temperatures between the top, middle, and bottom temperature sensor locations of the solar chimney remained at a high level. Since this testing scheme was in the "Air Blocked" position, the air remained trapped inside the solar chimney, therefore maintaining a thermal buffer throughout the nighttime hours.

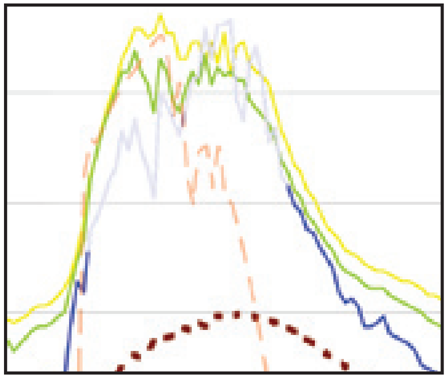


Figure 34.1. Test 1: Sunlight Filtered/Air Blocked enlarged graph.

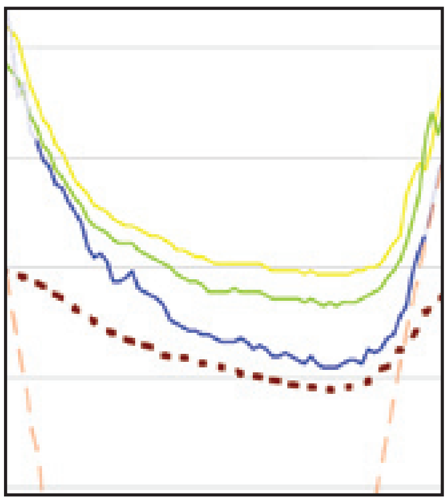


Figure 34.2. Test 1: Sunlight Filtered/Air Blocked enlarged graph.

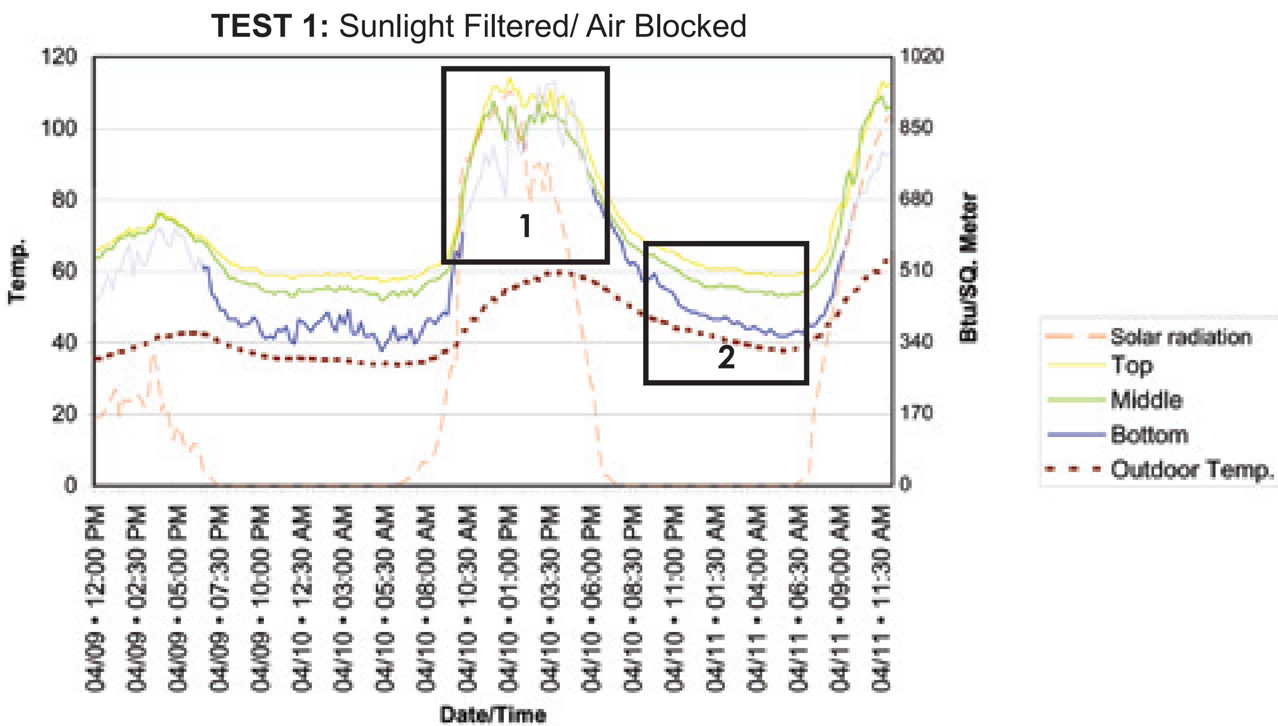


Figure 34.A. Test 1: Sunlight Filtered/Air Blocked graph.

During the daylight hours of test 3 (Figure 35.A. & 35.1.), the stratification of the air temperatures between the top, middle, and bottom temperature sensor locations of the solar chimney maintain a tight range compared to the "Air Blocked" position of Test 1 (Figure 34.1.). During the nighttime hours of test 3 (Figure 35.A. & 35.2.), the stratification of the air temperatures between the top, middle, and bottom temperature sensor locations of the solar chimney remained at a low level compared to the "Air Blocked" position of Test 1 (Figure 34.2.). Since this testing scheme was in the "Air Flow" position, the air exhausted out the top of the solar chimney, therefore allowing the solar chimney to shed solar heat gains.

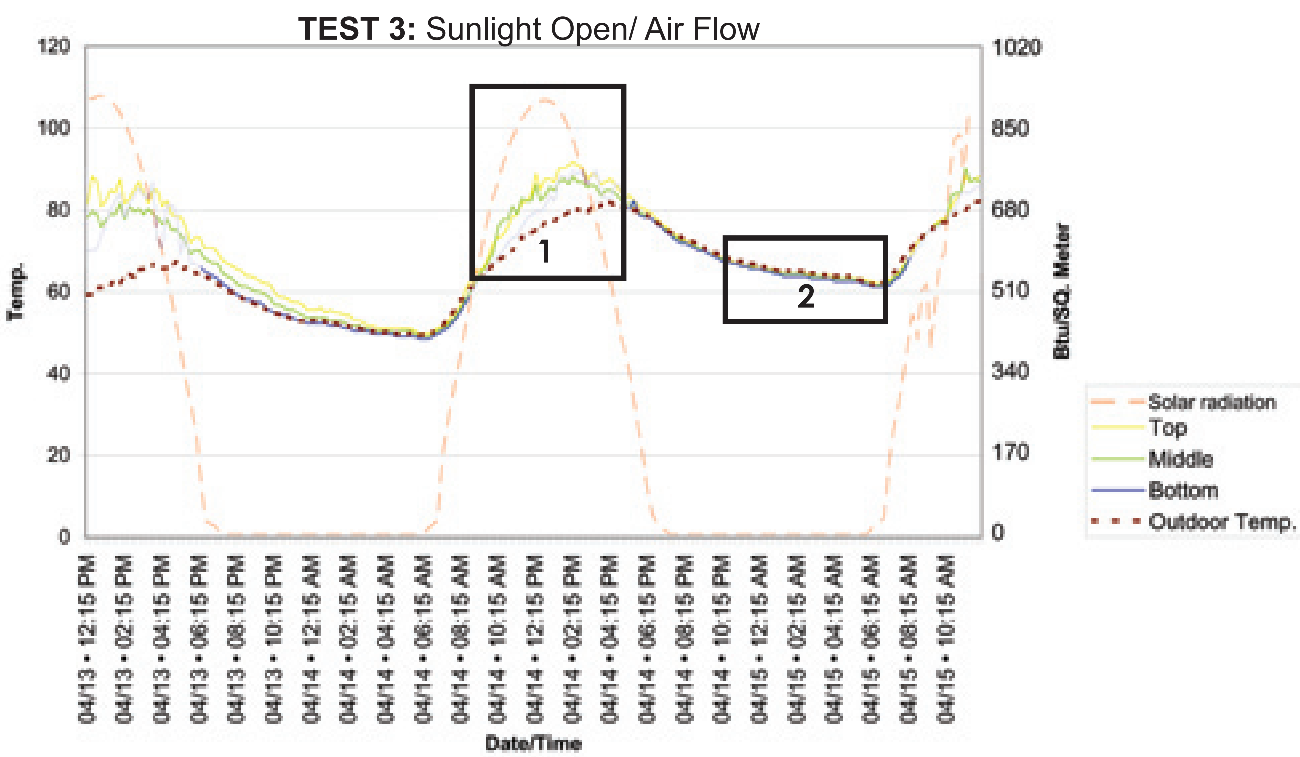


Figure 35.A. Test 3: Sunlight Open/Air Flow graph.

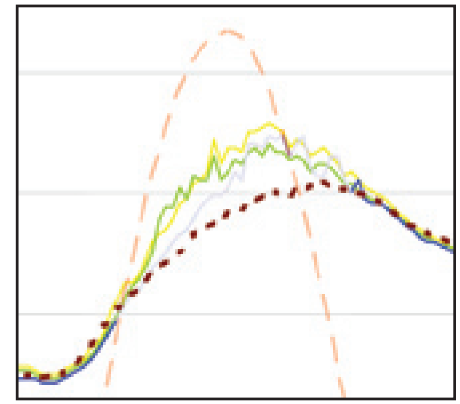


Figure 35.1. Test 3: Sunlight Open/Air Flow enlarged graph.

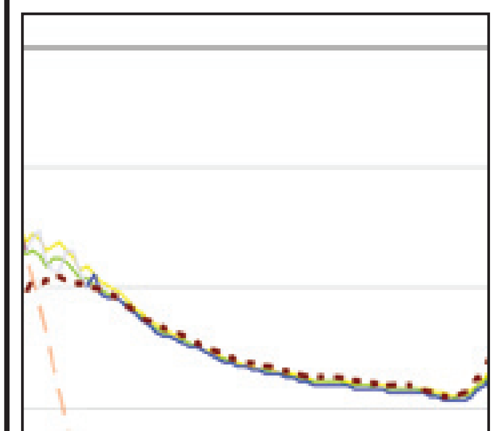


Figure 35.2. Test 3: Sunlight Open/Air Flow enlarged graph.

The comparison between test 3 - “Sunlight Open/Air Flow” and test 6 - “Sunlight Closed/ Air Flow” illustrates how solar radiation affects the change in temperatures within the solar chimney. During the daylight hours of test 3 (Figure 36.A. & 36.1.), the air temperatures between the top, middle, and bottom temperature sensor locations of the solar chimney continues to increase relative to the increase of solar radiation while the outdoor air temperature levels out. The air temperatures within the solar chimney continue to increase until the solar radiation level peaks. In the afternoon hours, as solar radiation decreases, the air temperatures within the solar chimney peak with a noticeable time lag and begin to decrease.

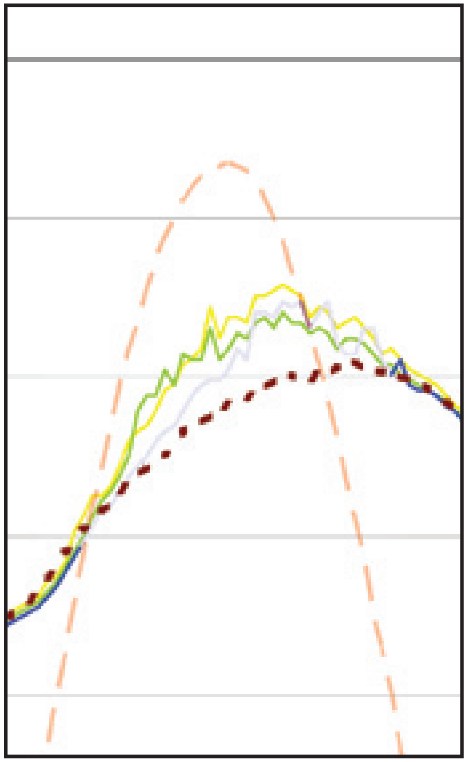


Figure 36.1. Test 3: Sunlight Open/Air Flow enlarged graph.

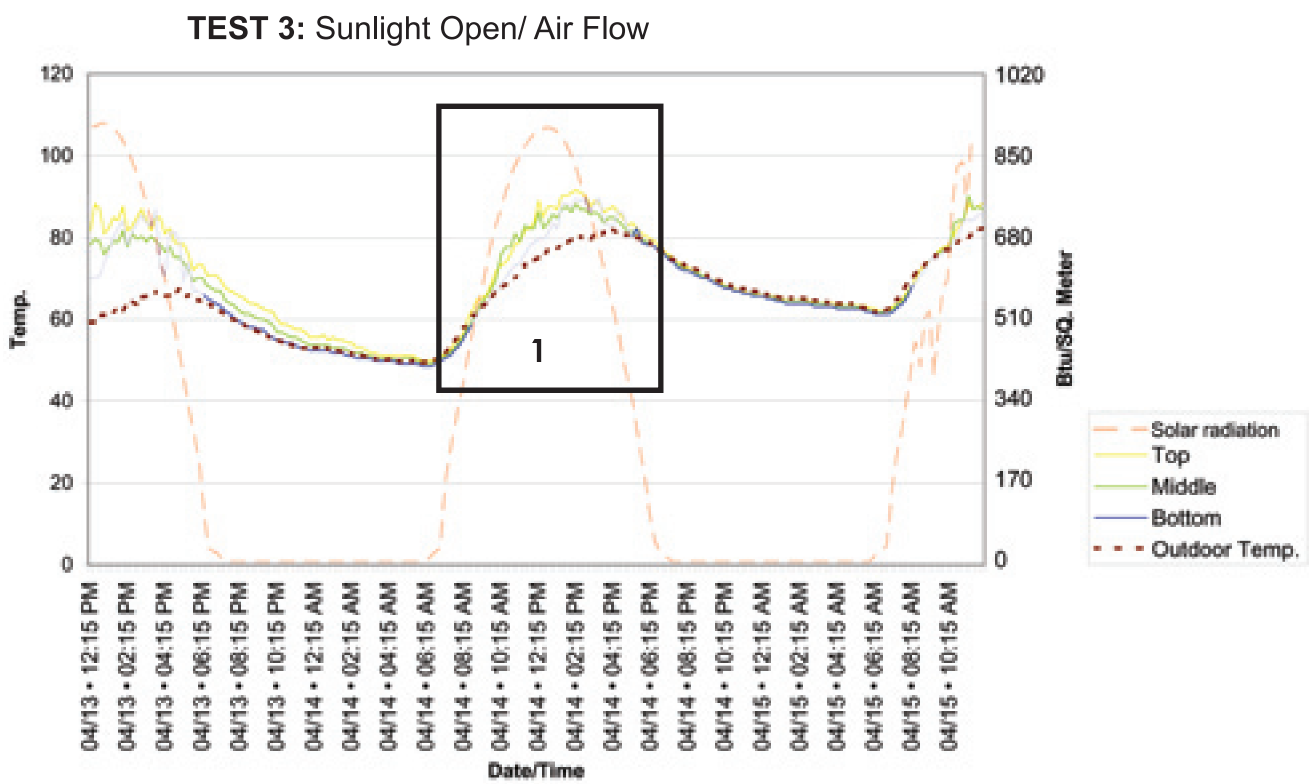


Figure 36.A. Test 3: Sunlight Open/Air Flow graph.

During the daylight hours of test 6 (Figure 37.A. & 37.1.), the air temperatures between the top, middle, and bottom temperature sensor locations of the solar chimney begin to increase relative to the increase of solar radiation, but the impact of cloud-cover on the solar radiation value causes fluctuations in temperature values. When a sudden decrease or increase in solar radiation occurred, air temperatures followed with a noticeable time lag, suggesting the impact solar radiation has on temperature fluctuation.

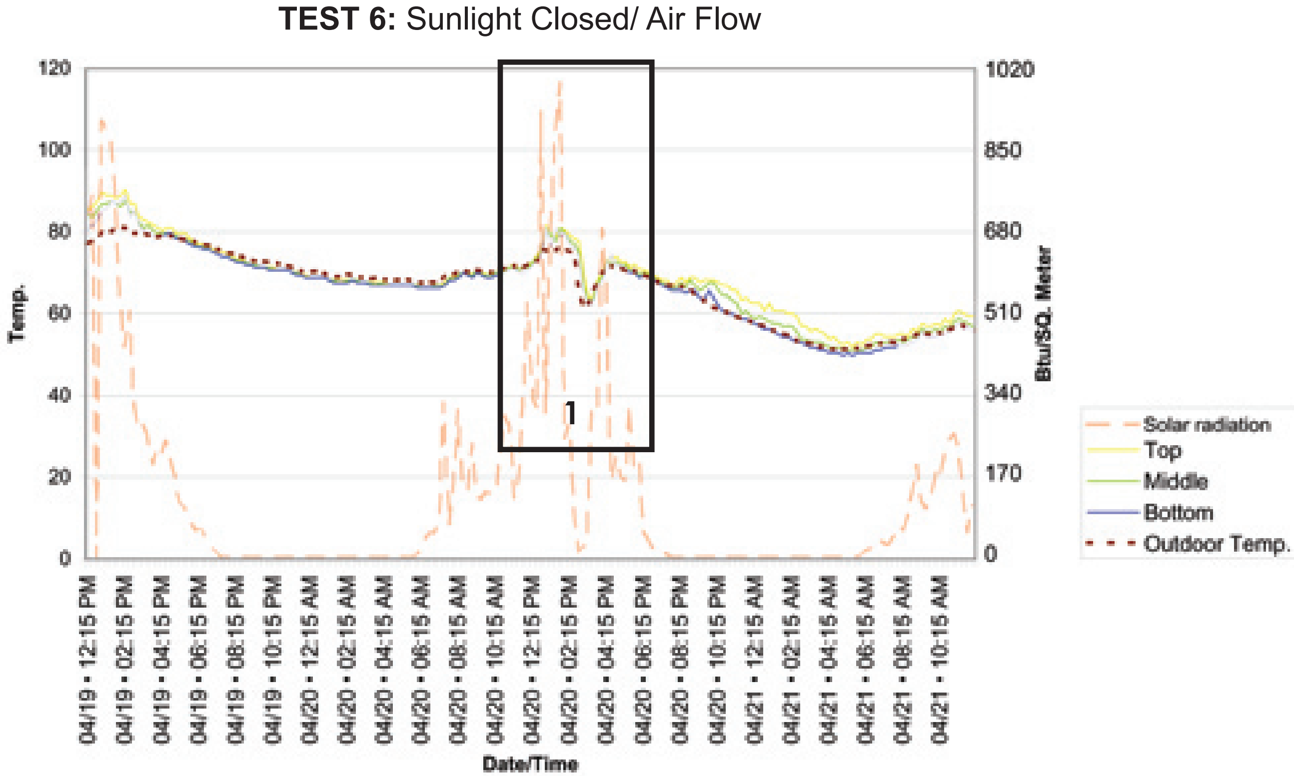


Figure 37.A. Test 6: Sunlight Closed/Air Flow graph.

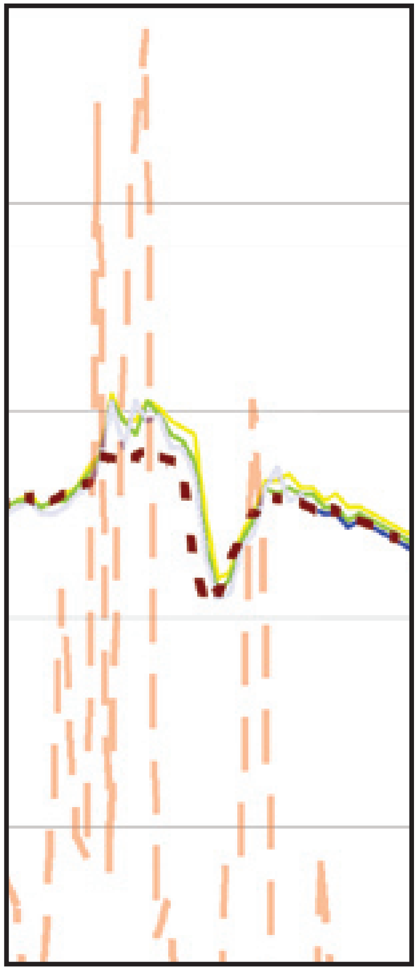


Figure 37.1. Test 6: Sunlight Closed/Air Flow enlarged graph.

Findings

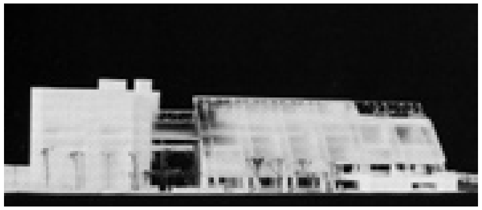


Figure 38.1. Winning competition model view from south. (Crumlish/Sporleder and Associates, Indiana Architect, June 1981)

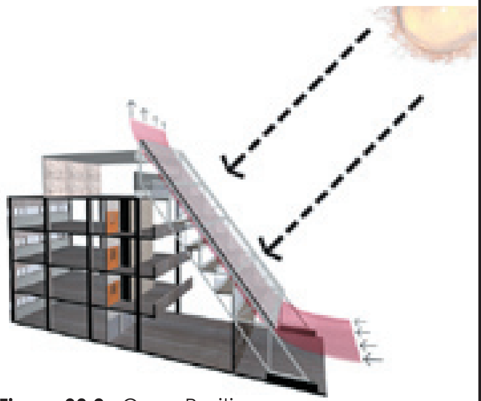


Figure 38.2. Open Position.
(Diagram by Steven R. Cook, 2003)

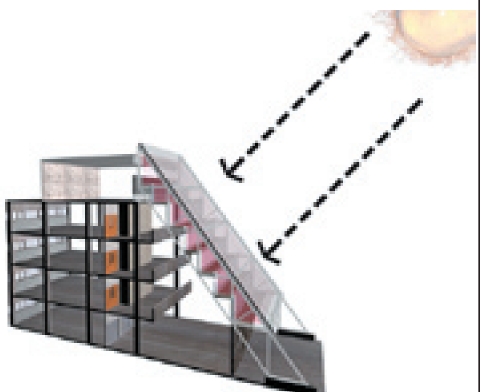


Figure 38.3. Closed Position.
(Diagram by Steven R. Cook, 2003)

The study of the College of Architecture and Planning's solar chimney began with a thorough investigation of the CAP addition's original design intent, as-built condition, and current operating condition. The information gathered during the research process provided insight into the solar chimney's daily operating schemes that utilize available natural energy sources. The study combined both the history of the CAP solar chimney and the data for its daily performance to gain an understanding of the complex system and make recommendations for the future use of the CAP solar chimney.

The original design by Crumlish/Sporleder Architects evolved from a state-wide design competition (1979) open to professionals within the state of Indiana (Figure 38.1). The addition to the Ball State University's College of Architecture and Planning building was to include 90,000 square feet of additional space, maintain a view to the south quadrangle, and to incorporate the use of passive and active solar design strategies. The "solar chimney" was originally submitted as a design alternate in lieu of a single-glazed façade, and was ultimately chosen because some of the proposed active solar equipment would not fit within the available budget.

The CAP solar chimney was designed to operate using the stack effect principle—hot air's natural tendency to rise. The stack effect is what drives the various operating schemes of the solar chimney. Between the two layers of the sloped roof is a volume of air that is either rising while the chimney is open, or stagnant when the chimney is closed.

In the open position, the sun heats the volume of air that is inside the chimney cavity. (Figure 38.2) Due to the stack effect, the heated air rises out the top of the sloped roof, while drawing cooler air in at the bottom. The resulting flow of air cuts down on heat gains by continuously removing stored heat off the building's façade and exhausting them out the top of the solar chimney.

In the closed position, the sun heats the volume of air that is inside the chimney cavity, but because the louvers are closed, the air is trapped and continues to be heated (Figure 38.2). This scheme is used during colder seasons to create a temperature buffer between the extreme air temperatures of the outdoor and indoor air temperatures.

The CAP solar chimney was designed to have different operating positions depending on the weather conditions on a particular day (wind direction, wind speed, cloud cover, and air temperature). Although these schemes work, they primarily rely on manual operation which became too cumbersome to monitor and/or control on a daily basis. Although the design of the solar chimney's operating schemes were successful, the as-built condition modified the original design intention. Perhaps the most significant difference is the failure to connect the solar chimney with the building's mechanical system for use as an air intake "pre-heater." A minor modification made to the original design was the use of eutectic salt tubes in lieu of eutectic salt bags shown in the original construction documents. The round shape of the eutectic salt tubes provided more surface area to be exposed to direct solar radiation allowing solar energy to be more effectively stored. One of the major negative aspects of the as-built condition of the solar chimney is the limitation of technology available at the time of construction. An automated control system was installed, but the components quickly became obsolete and unavailable due to the rise of computer technology in the early 1980's, resulting in a complex system to be manually operated.

During the past 20+ years, the solar chimney has undergone a few modifications and currently exists in a dormant condition. The eutectic salt tubes were removed due to problems with leaking, which caused a potential threat to the tectum panels that make up the horizontal stepped surfaces of the solar chimney. The manually operated windows located in the design studios, which provide the fresh air intake for the natural ventilation scheme were bolted shut because of pressure differences within the building that were interfering with the building's mechanical systems. Permanently sealing the operable windows eliminated the potential for natural ventilation to occur. Even though the solar chimney exists in a dormant condition, almost all of the components of the system are still operable with the exception of one section of dampers and the motorized horizontal blinds in the 1st (west) bay. The other two bays of horizontal blinds are functional, but are not all in sync with each other, resulting in varying amounts of solar radiation penetrating the building.

Over the years, the solar chimney has proven to be a rather complex system to operate with its reliance on manual input for daily operation. Since most of the components of the solar chimney are still in place and operable, the Ball State University's Facilities Management Department is willing to update the components of the solar chimney to perform to the best of its ability for use as an active double-skin façade without the use of the natural ventilation strategy. The upgrade would involve getting the entire solar chimney and all of its operating components online with a system that would not only monitor the components, but also control them.

A two-week test of the solar chimney's daily temperature behavior was conducted during the 2003 Spring Semester starting on April 9th and terminating on April 21st. The tests were created and conducted by Steve Cook and Bob Patton with the assistance of Bob Koester, Dave Bartle, Jeff Culp, and Alfredo Fernandez. The test of the solar chimney was conducted in the 3rd (east) bay using Stow-Away temperature sensors placed at bottom, middle, and top locations throughout the double-skin cavity. The Stow-Away sensors recorded local temperatures in 15 minute intervals allowing for thorough observation of the temperature fluctuation throughout the day and night. Six different testing conditions were created by adjusting the horizontal blind positions and opening and closing the top and bottom air dampers.

The two week test period did provide useful information about the behavior of the solar chimney, but some observations were noted about what could have been done to provide more accurate test results. (1.) The individual tests should have been conducted for a longer period of time. Ideally, the tests should have been conducted during various weather conditions and throughout all seasons of the year to get a more accurate observation of the solar chimney's behavior. Unfortunately, due to time constraints, longer testing periods were not possible for this study. (2.) The changes made for each test occurred at noon, which seemed to cause some inconsistency in temperature recordings. The changes should have been made at midnight rather than at noon because of the presence of solar radiation during the daytime hours. The changing of the tests in the middle of the day resulted in abrupt temperature changes that disqualified some data at the beginning of each test. (3.) Another circumstance that affected the resulting data was the exposure of direct sunlight to the bottom Stow-Away sensor after the tests had already begun. The sensor's remote sensor wire became twisted and rotated its sun-shield in the wrong direction (Figure 39.1). On clearer days, the bottom sensor read consistently higher than the other sensors that were shielded from direct exposure to sunlight throughout the entire testing period(Figure 39.2).

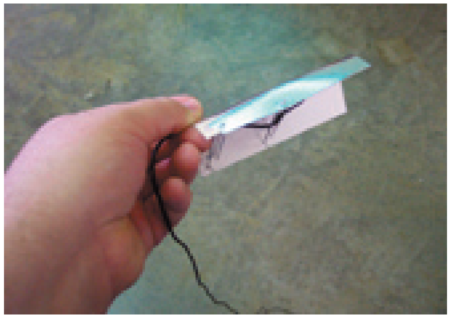


Figure 39.1. Detail of sun shield and wire sensor.
(Photo by Robert J. Patton, 2003)

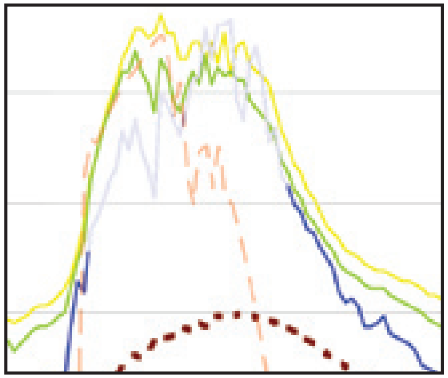


Figure 39.2. Enlarged graph showing irregular tracking of bottom StowAway sensor (blue line).

Summary

Figure 40.1. Scale Demonstration Model
(Photo by Robert J. Patton, 2002)

The purpose of researching the College of Architecture and Planning building's solar chimney was to study the behavior of double-skin building facades systems at a full scale. During the fall semester of 2002, Steve Cook and Bob Patton investigated the principles of double-skin façades during a renewable energy class instructed by Dr. James Eflin. After researching case studies and identifying the principals behind various double-skin facades, a 1"=1' scale model was designed and constructed to demonstrate the behavior of double-skin façade systems (Figure 40.1). Even though the 1" scale model provided a useful tool for demonstrating the principles of double-skin facades, the full scale solar chimney proved to be beneficial for gathering information about the real life behavior of double-skin building façade systems.

As the study of the solar chimney began, the Ball State University Facilities Management department further justified the purpose of this study by showing an interest in revitalizing the solar chimney for a more effective future use. The information gained from testing the behavior of the solar chimney may end up being used by the Facility Management department to reactivate the system to its fullest potential. If the solar chimney were to be completely automated and computer monitored, guidelines based on the data of the solar chimney's daily behavior could be established to allow for optimum performance.

The two week testing period allowed for the observation and documentation of temperature behavior inside the solar chimney. The results from the testing revealed how the solar chimney is affected by solar radiation and outdoor weather conditions. Another factor in testing the solar chimney was to gain an understanding of how the solar chimney behaves when the top and bottom louvers are opened or closed and while the horizontal blinds are open, partially open, or closed. The StowAway sensors placed at the top, middle, and bottom locations within the solar chimney cavity and the outdoor temperature recordings at 15 minute intervals from Alfredo Fernandez-Gonzalez's research, provided the necessary data to analyze temperature stratification between the temperatures within the solar chimney cavity and the varying outdoor temperatures.

Due to time constraints, careful thought was invested into the design of the tests in order to manipulate and test six different operating schemes, each lasting two days and nights for a total of twelve days. Each operating scheme was set up in accordance with the solar chimney's allowable operating condition involving opening and closing the top and bottom air louvers and adjusting the sun shading blinds within the solar chimney cavity. The StowAway sensors, recording temperatures at the bottom, middle, and top locations within the solar chimney at 15 minute intervals, allowed for the production of a series of graphs displaying data from the 12 day testing period. The solar chimney temperature compared to the outdoor temperature and solar radiation levels revealed how the solar chimney responds to changing weather conditions.

Based on our initial research, the following hypotheses were formed:

1.) The CAP solar chimney is an effective design strategy that regulates and controls solar gains throughout the day.
2.) The activation of (A) top and bottom louvers and (B) motorized sun-shading blinds impacts the daily performance of the CAP solar chimney.

The first hypothesis was proven to be correct in that the solar chimney successfully removed excess solar gain and created a temperature buffer. The second hypothesis consisted of two factors: Part A was proven to be correct, while part B was proven to be incorrect. For part A, the opening and closing of the top and bottom louvers produced vast differences in behavioral data, while part B, the positioning of the horizontal shading blinds produced little to no difference in the solar chimney's behavior.

In hindsight, one observation is that although the positions of the motorized blinds were characterized with the terms 'open', 'filtered' and 'closed' it should be noted that the terms may not fully represent the true position of and, in turn the performance of, the blinds. In fact, the blind position that was termed 'open' is instead the same as the 'filtered' position with the blind tines adjusted to tilt upward towards the arc of the sun through the sky. In fact, because of the arc of the sun throughout the day, in this position, the blinds perform similarly to the stated 'filtered' position with the blind tines positioned horizontally and also similarly to the blinds in the 'closed' position. In each case, at various times, the blinds are intercepting a significant portion of the direct sunlight attempting to pass through the double wall and into the atrium space. A more true representation of a blinds 'open' position might have been to retract (raise) the blinds to allow a more unobstructed penetration of direct sunlight through the double wall and into the atrium space. However, this type of blind adjustment (retraction) was not available during the study. This, in part, could explain the minimal influence of blind position on the measurements recorded.

Overall, the solar chimney fundamentally performed much like any double-skin façade system by creating a thermal buffer between indoor and outdoor temperatures. Perhaps the most significant conclusion made from the testing was the effect that solar radiation has on the temperature within the double-skin. The temperatures within the solar chimney cavity responded directly to the increase and decrease of solar radiation levels rather than changes in outdoor air temperature.

The testing of the solar chimney proved several assumptions made about the behavior of double-skin façade systems. (1.) Air temperature does stratify within the solar chimney cavity. The temperature recordings throughout the majority of the testing period increased slightly from the bottom, middle, and top locations respectively. The nature of the double-skin therefore promotes natural ventilation with the rising of warm air within the solar chimney cavity. (2.) Air flow does reduce heat gains within the solar chimney. When the air louvers were in the open position, the stratification between the outdoor air temperature and temperatures within the solar chimney was much less than days when the air louvers were closed. (3.) Trapped air within the solar chimney does create a temperature buffer between indoor and outdoor temperatures. The night time temperatures within the cavity of the solar chimney consistently remained higher than the decreasing outdoor air temperatures proving that the solar chimney does create a thermal buffer. (4.) Solar radiation is the most influential factor that affects the behavior and performance of the solar chimney. Temperatures within the cavity of the solar chimney would still elevate to high levels when the outdoor air temperature was low and the solar radiation level was high. (5.) The sun shading blinds influence on the solar chimney's behavior is minimal. The data did not indicate any significant variation in temperatures within the solar chimney due to altering the position of the shading blinds. Therefore, the blinds should only be used as a way to control glare and indoor daylighting needs.

The tests proved that the solar chimney is an effective green building strategy. The double-skin does create a thermal buffer between indoor and outdoor air temperatures, which can lessen the amount of energy needed to heat or cool a building while allowing an abundance of daylight to enter the building. Even though solar chimneys rely on natural energy sources to function, they can be expensive to build and maintain. If a solar chimney is operated and maintained properly, it is likely that the cost of constructing such a system will be outweighed by the reduction of the building's energy costs over time.

The results from the tests only represent a glimpse of the solar chimney's annual performance; however, based on the insights gained from testing the solar chimney's behavior, recommendations can be made to suggest how the solar chimney could effectively operate under its current condition. Natural ventilation schemes are not desirable due to the locked windows, but the primary buffer schemes would work well. In order to effectively resurrect these schemes, the top and bottom air dampers must be motorized to respond to solar radiation. Most of the components of the solar chimney are already operable, so integrating the motors with a completely automated, computer monitored system would not be require a significant amount of remodeling. Solar radiation and temperature sensors within the solar chimney would also have to be installed to monitor the conditions that affect the performance of the solar chimney. The solar radiation sensors would operate the dampers, while the temperature sensors would determine the appropriate operating scheme for which the solar radiation sensors would then respond.

Once all of the automated components and sensors are installed, a schedule would need to be established in order for the solar chimney to know when to open or close. This schedule could be made by executing the tests illustrated in this study and determining the range of temperature in which the solar chimney should remain open and when it should remain closed. The system should be completely automated so no manual input is required for daily operation, however, the system should include a manual override for educational and demonstrative purposes.