# AN EXPLORATION OF THE NATURAL VENTILATION STRATEGIES AT THE WORLD TRADE CENTER AMSTERDAM

By

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**An Exploration of the Natural Ventilation Strategies**
**At the**
**World Trade Center, Amsterdam**

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**(Abstract)**

The push to design environmentally conscious and sustainable buildings has surged over the past twenty year, thus leading to the development of new methods for harnessing the natural elements of the earth. In recent years the international firm of Kohn, Pederson and Fox has been a champion of the sustainability movement. In fact many of the newer passive ventilation strategies under development can be seen in Kohn, Pedersen Fox International **(KPFI)** current commission for the World Trade Center (WTC) currently under construction in Amsterdam, Netherlands. This multi-million square foot complex has been designed to service the growing needs of Europe's free market economy and the fledgling European Union (EU). The complex is a series of five towers with connecting multi-storied atriums in the interstitial spaces. While the towers are actively heated and cooled using modern energy efficient systems the atrium areas are ventilated using an innovative passive system. This passive system relies on turbulence and negative pressure along the roof system to draw air through the space and positive pressure (due to wind driven forces) at the inlets located above the ground level doors to bring air into the atrium. The primary concept behind this strategy is that the difference between the positive and negative pressure zones will induce a convective current within the atrium space and there by create a continuous air-change system. The intent of this thesis is to analyze and report on the findings of the wind tunnel tests done on scale models of the complex and, propose alternative ideas to strengthen the current design.

**ACKNOWLEDGEMENTS:**

This document is dedicated to my parents Allen and Jeanne West for all the support they have given me in my academic pursuits. Likewise a great deal of thanks goes out to my sister Christy West and my closest friends Matt Symons and Sean Stansell for all their help.

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I'd like to express my deepest appreciation to my committee members Yvan Beliveau and Bob Schubert. Your insight helped me to define the parameters of this study and kept me on track.

Of course this project would have never gotten off of the ground without the help of Kohn, Pedersen Fox International out of London. Special thanks goes to Lee Polisano, a fellow Hokie, and principle of the London Office for allowing me access to such an interesting building. Also a great deal of thanks goes to Ian Milne, the project manager for the WTC project for KPF. Through the course of this study your insight on the building has proved to be extremely beneficial. In all though words cannot express my gratitude to KPF and Battle-McCarthy Engineers for giving me a peek at cutting edge technology at work.

Finally, I come to Jim Jones. Over the past 2-½ years at Virginia Tech I've had the great pleasure of working in close relation with you on a variety of projects. All of which have helped to increase my wealth of knowledge in the building sciences. Oh yeah, and of course Big 10 football!

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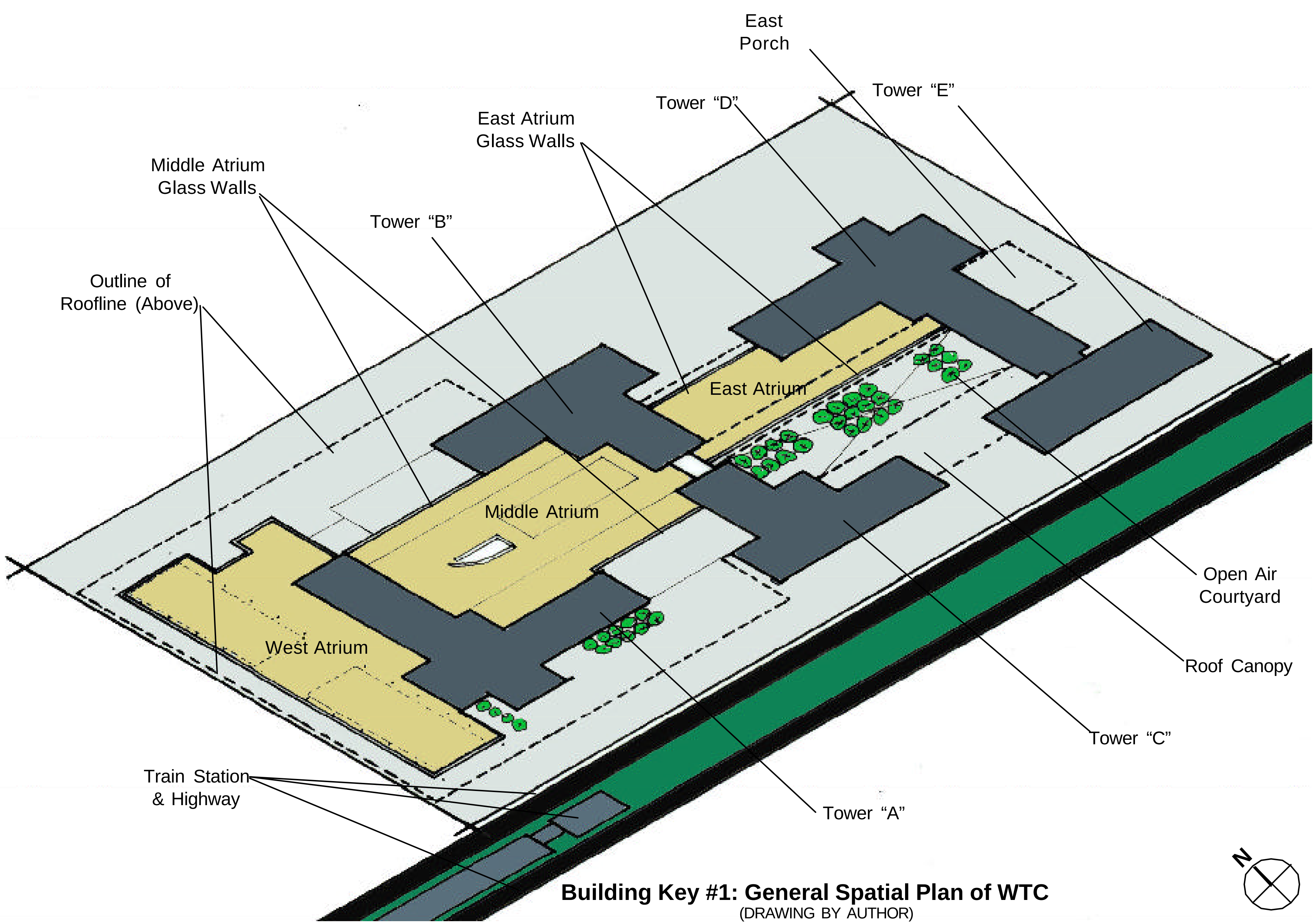
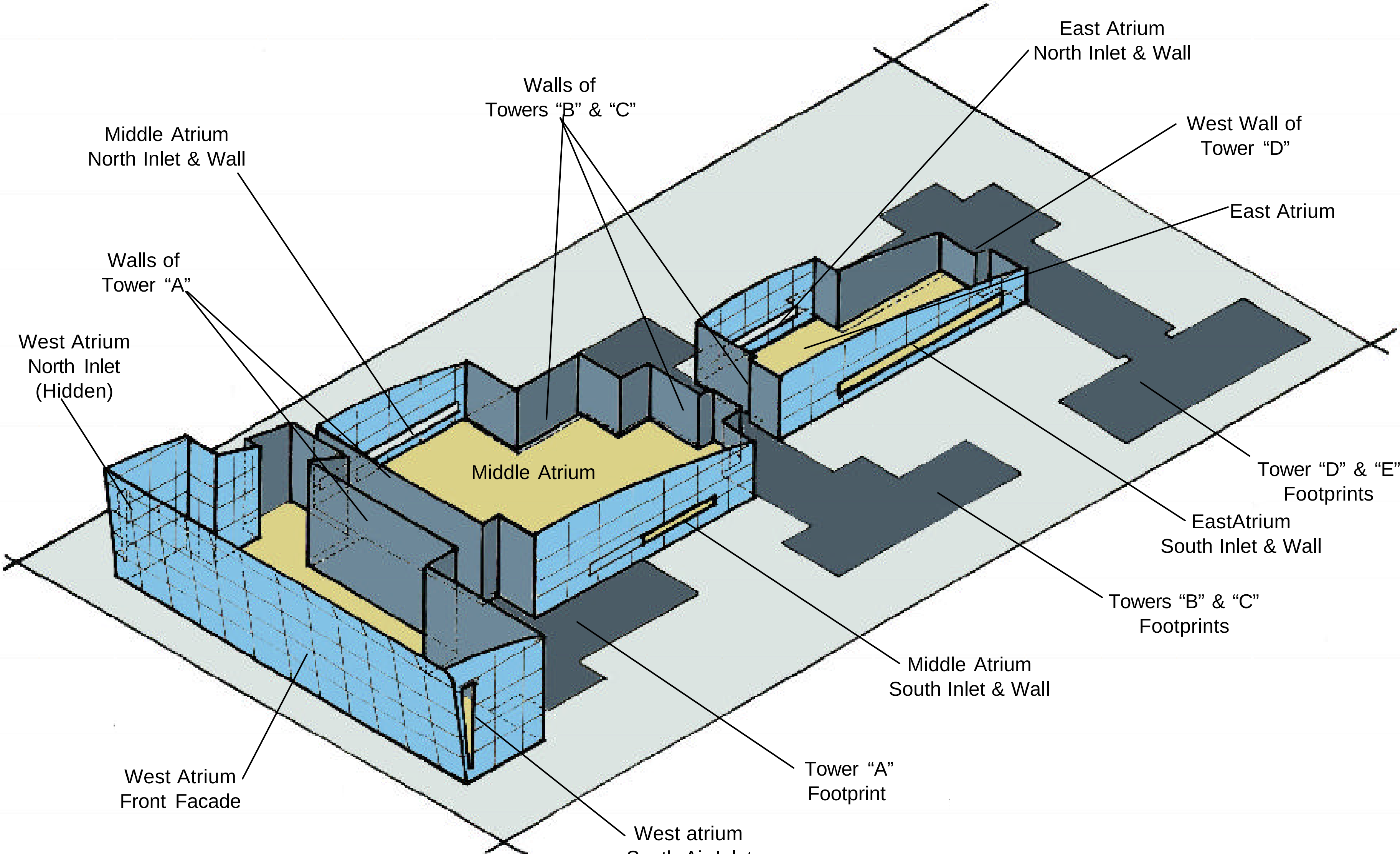
## Building Key Plans

The following four pages are meant to serve as a graphic break down of the major elements of the World Trade Center in Amsterdam. Each drawing emphasizes a critical concept in the new design by Kohn, Pedersen Fox. **Building Key #1** focuses on the spatial arrangement of the complex. **Building Key #2** shows the major atrium spaces in three dimensions while noting the air intake locations on the north and south walls. The third page, **Building Key #3**, incorporates the roof system and shows the location of the exhaust ports on the central spine of the roof. The fourth and final drawing, **Building Key #4**, shows the complex in as a series of simple masses and incorporates the towers as the dominating feature of the site. These drawings are to be used as a quick reference while reading through this document, especially during the discussion of the complex in Chapters 2 and 4.




**Building Key #1: General Spatial Plan of WTC**
(DRAWING BY AUTHOR)




**Building Key #2: Atrium Locations Showing Wall Inlets**
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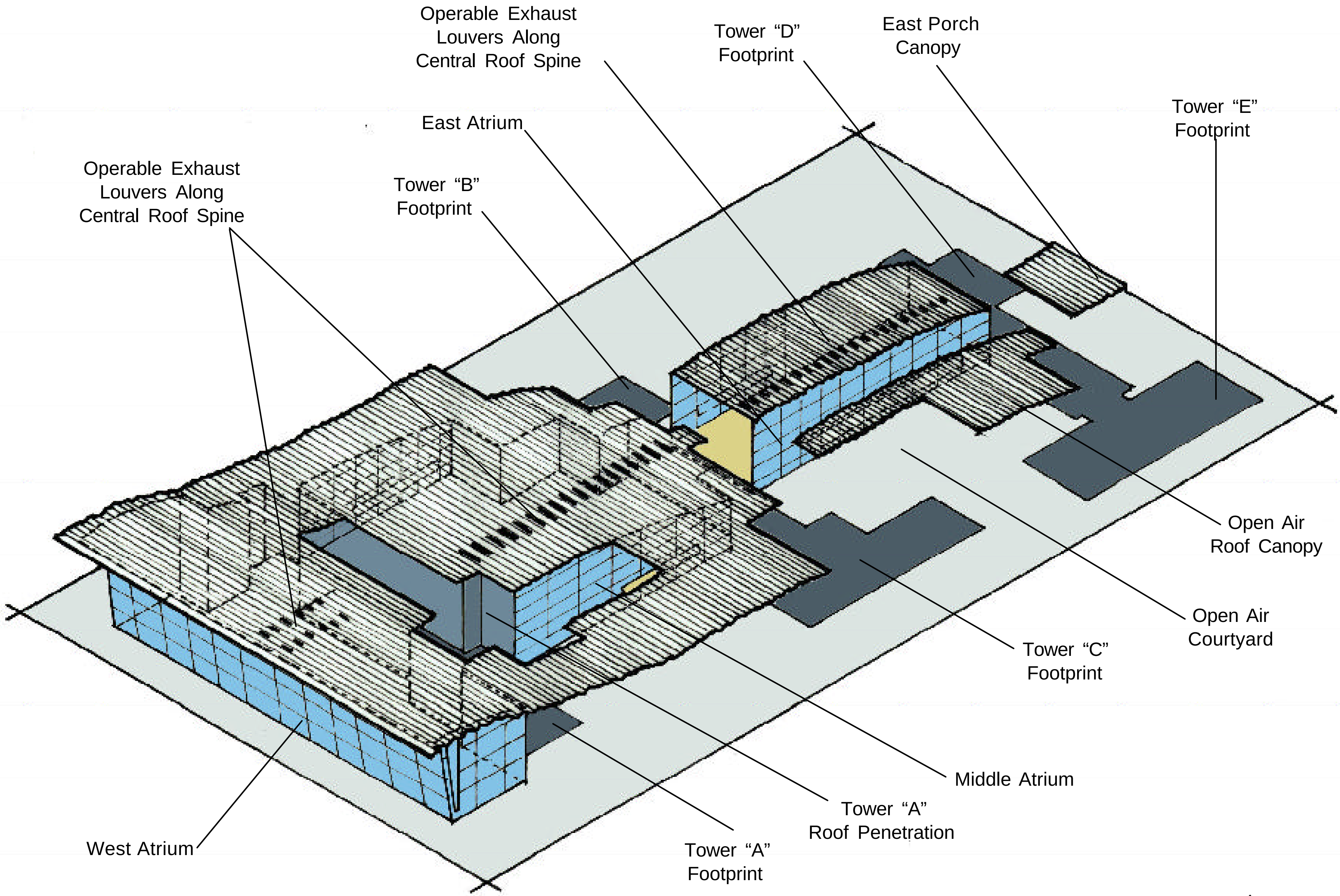
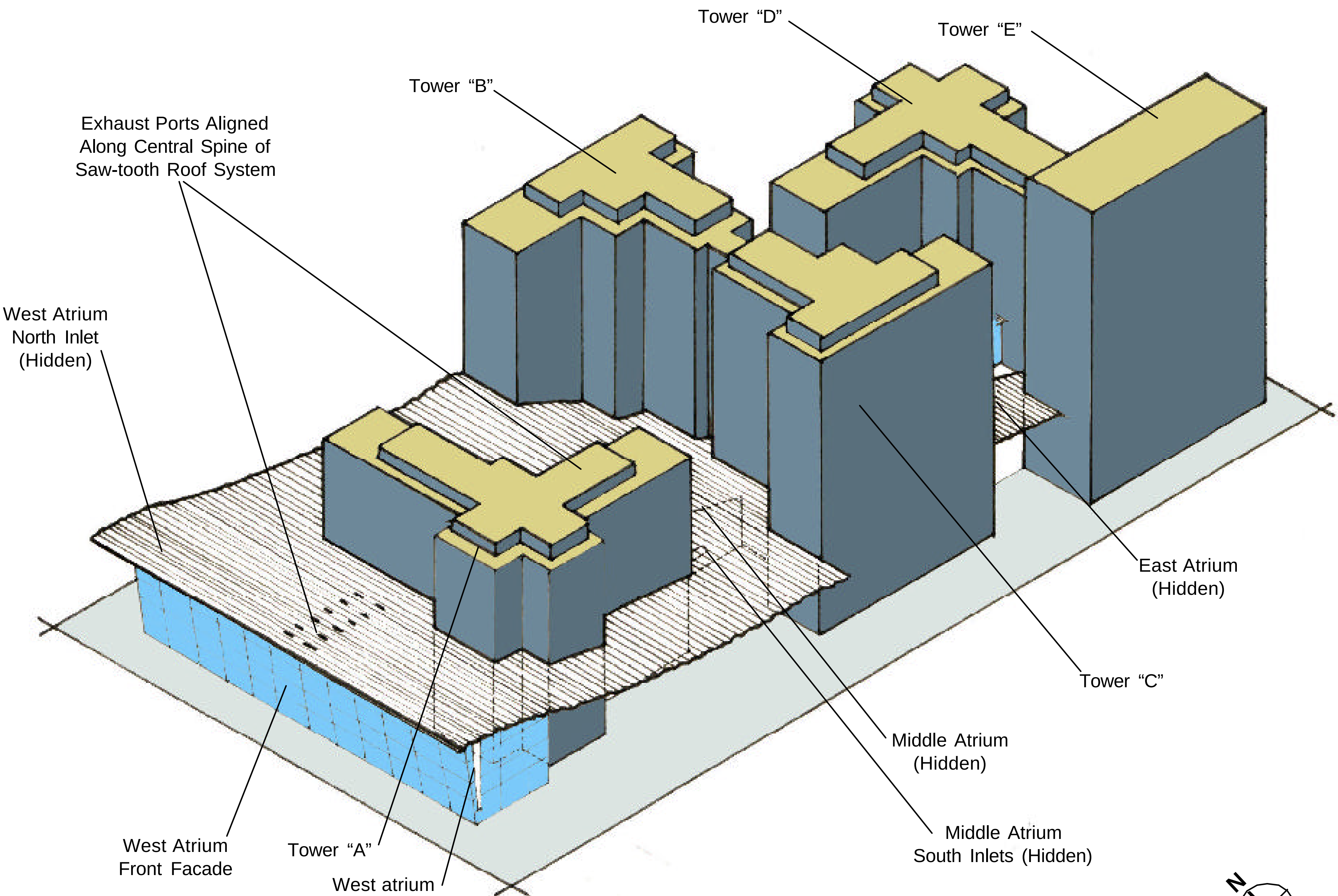



**Building Key #3: Roof System In Relation To Atriums**
(DRAWING BY AUTHOR)




**Building Key #4: Full complex including all components**
(DRAWING BY AUTHOR)

## Chapter 1: Introduction

In the late fall of 1997 the Building Science faculty from the College of Architecture at Virginia Tech were invited to travel to London. The purpose of the visit was to tour the London office of Kohn, Pederson & Fox as well as view a few of their current projects that had recently been built in England. Their host was Lee Palisano, the principle in charge of the London office and a Virginia Tech graduate. While overseas the architecture faculty and Palisano vowed to begin a dialogue that would hopefully lead to joint efforts between the College of Architecture and Urban Studies (CAUS) and KPFI. In 1998 the London office of KPF won the design competition for the renovation of the World Trade Center in Zuid Amsterdam with a spectacular series of towers and atriums. The towers were to utilize the relatively new double envelope technology and the atriums were to use the most cutting edge methods in natural ventilation. In an effort to initiate this collaborative relationship faculty in the CAUS offered to investigate and document natural ventilation strategies used in this building.

In early 1999 KPFI provided electronic drawing files showing the main floors of the atriums, critical sections, elevations and detailed 3-D sections of the complex. After initial study many questions were raised about the effectiveness of the atrium ventilation system and how the height of the towers would affect these systems. With this as the basis for the thesis, models were developed of the project to be studied in the wind tunnel facility on campus. The following pages, images and data summarize the study on the World Trade Center complex.

The following are the objectives, assumptions and the hypothesis of this study:

### 1.1 Objectives:

1. To better understand the ventilation strategy as designed by KPF, International for the World Trade Center in Amsterdam
2. To validate KPF's assumptions that a negatively pressurized roof system will create the necessary draw to ventilate the atrium spaces.
3. To determine whether or not KPF's roof design is true to its functional requirements or more a formalistic representation of the ventilation requirement.
4. To determine the flaws, if any, in the WTC design and subsequently propose modifications to solve said problems
5. To determine whether the towers will create dead spots along the atrium roof edge.
6. To determine if alternative measures can create an increased performance at the roof system

### 1.2 Assumptions (Related to methodology):

1. That the wind tunnel analysis is a reasonable approximation of real world conditions

### 1.3 Hypothesis:

1. The efficiency of the saw tooth roof design will be related to the air speed along the roofline.

    1) $\mathbf{AF_{int} = b_o + b_i\, AF_{roof}}$

    Where:

    $\mathbf{AF_{int}}$ = Airflow rate interior
    $\mathbf{AF_{roof}}$ = Airflow rate on roof

2. That the inclusion of an additional roof system to induce the stack effect and the Venturi effect will increase the efficiency of the atrium's ability to move air.

    2) $\mathbf{M_1 - M_0 > 0}$

    Where:

    $\mathbf{M_1}$ = Ventilation rate with modified roof
    $\mathbf{M_0}$ = Ventilation rate as designed

## Chapter 2: Introduction and History of Natural Ventilation

### 2.1 The History of Natural Ventilation

From the dawn of time mankind has continuously attempted to harness the natural elements of the earth for his own benefit. Fire was contained and provided heat and light while earth and water were recognized for their life sustaining qualities. Wind however was a different matter. In ancient cultures the wind was often seen as the bearer of bad things, cold air from the north, hot humid air from the south as well as the bringer of disease and pestilence. In the Age of the Roman Empire the evils of the winds were discussed in great depth in the first great tome of architecture, "The Ten Books of Architecture". The "Ten Books" were the creation of the personal architect to Augustus Caesar, Vitruvius who through the course of his writings set out the principles for Roman building, the laying out of cities, the creation of war machines as well as a detailed treatise on the various types of building materials available to the Romans. Vitruvius also dealt a great deal with the containment of the winds during the laying out of a city in his book.

#### 2.1.1 Vitruvius

According to legend Vitruvius noted that there were four primary winds, and four secondary winds a fact, which was reinforced by the octagonal tower of Andronicus in Athens.[1] For according to history each face of the tower represented the humanistic characteristics of the complimenting wind engraved upon it. According to Vitruvius there were four primary wind directions or quarters. These quarters translated into modern language are the four Cardinal directions, North, South, East and West. He also defined the secondary winds as those, which blew from the direction halfway between two quarters, Southwest, Northeast and so on. With the basic wind directions and properties firmly established Vitruvius then set out to describe the proper way to lay out a city. The first step was to identify the major winds and from which direction they came and then mark the center of the city accordingly. Cold winds were disagreeable to man and were to be avoided, likewise hot \ humid winds were unhealthy and Vitruvius felt that it was good

**Figure 2.1. Tower of Andronicus (Morgan 1960)**

[1] Vitruvius, The Ten Books Of Architecture, trans. Morris H. Morgan (New York, Dover, 1960) pg 26

practice to shut out all winds for health purposes.[2] Accordingly common sense at the time stated that a thick air of mild temperature and without draught was good for building up one's fortitude and restored those afflicted with disease. Thus it was absolutely crucial that the predominant winds were identified. From this central point all roads were to be laid out on axis between two quarters so that the winds would be funneled down the streets and alleyways. The laying out of roads in this manner also prevented the winds from blowing head on into the facades of the buildings lining the streets and thus keeping the winds out of the dwelling spaces. Vitruvius noted that an even better method for laying out the city streets was to orient the buildings along the street slightly off axis in an effort to disturb the winds path as it blew through and to "*kill off it's harmful nature*".

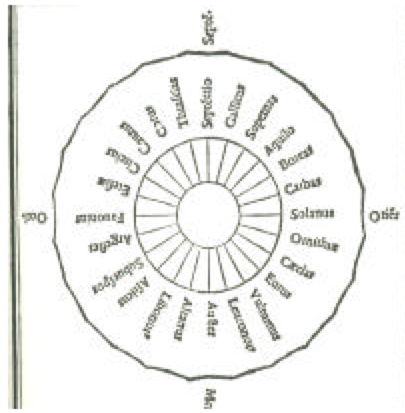



**Figure 2.2. Vitruvian Wind Dial (Morgan, 1960)**

While Vitruvius' writings explained the proper method of laying out a city, they do have a more important role in the regards to this study. Vitruvius' "Ten Books of Architecture" are widely credited as the first written record of architectural thinking in the history of our existence and likewise Vitruvius is also the first (by default) to address the winds as a field of study, which we now call fluid dynamics. For in his writings on the city Vitruvius broaches three very critical concepts in fluid dynamics. First that wind will flow along any path that is provided for it. Second, that wind funneled into smaller or tighter spaces from a larger space will increase in velocity and finally that obstructions in the wind's path will substantially decrease its velocity and effect.

Vitruvius' understanding of architecture and the elements served as the guiding force for building in Europe from the days of the Roman Empire up to the Renaissance. However his basic notion on the evils of the winds is for the most part fallible. Common knowledge and common sense throughout Europe even on the most basic of levels said that some of the breezes were beneficial to ones health and well being. While the cold winter winds were and still are considered undesirable, the summer breezes were seen for their potential cooling effect. In houses all across Europe openings were cut into the walls that faced the prevailing summer breezes to allow the fresh air in and hopefully expel the unhealthy air. While this proved somewhat effective it was soon realized that by adding another opening directly opposite the first opening would allow the breezes to carry through the house unimpeded, and thus push out the stale air. In order to keep unwanted winds out, operable shutters were developed to close off the openings when desired. This method was the first understandable method for cooling a home. Likewise this method of cross ventilation is still one of the most widely used approaches to natural ventilation to this day.

[2] Vitruvius, pg 27

### 2.1.2 Natural Ventilation In Hot Arid Climates

In the hot arid climates of Northern Africa and the Middle East the winds were generally desirable, as they were the only way to cool remove hot stagnant air. However in this desert region different methods were needed to tap into the winds for cooling. Unlike European housing of the time, desert homes were often made of thick stone or adobe walls with high thermal mass to keep the heat of the day out and the collected heat in during cold nights. Consequently it was often very difficult to cut in window openings on street level. Offensive odors, dust and trapped heat on the street level could enter in through any of these lower level openings and would be more of a detriment to ventilating the house than a benefit. Thus most openings were placed high near the flat roofs but even then they were used only for lighting.

It was well known that the breezes that moved across the rooftops were much cooler and cleaner than those at street level (especially in the evening). The design challenge was to capture the high-level breezes, reroute them into the occupiable space and then vent the stale air back out doors. The result was a system of two towers, one a wind scoop to capture and redirect the air and the other a wind tower to extricate the air. This two-tower system was called a "malqaf" and a later hybrid one-tower system called a "badgir" was developed. In the malqaf design one wind scoop was oriented so that it's opening faced the prevailing winds. As the wind blew into the scoop it was forced down the shaft into the living quarters.[3] In some instances damp fabric was placed in the intake tower to act as an evaporative cooler. The exhaust tower was generally located on the opposite side of the house from the intake tower. Unlike the intake wind scoop the exhaust tower was an open stack with a small raised cap over the exhaust port. The pressure difference between the inlet and exhaust towers was generally enough to draw the stale air out.

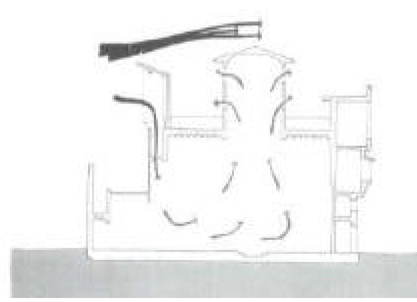


**Figure 2.3. Typical Malqaf Diagram (Battle-McCarty 1998)**

### 2.1.3 Monticello

Another historic example of natural ventilation is at Monticello, the mountain top home of Thomas Jefferson. In addition to being an accomplished diplomat Jefferson was one of the first true great American architects. While formally trained in law, Mr. Jefferson was a veritable Renaissance man who

[3] Wind Towers: Battle McCarthy Consulting Engineers, Details In Building (New York: John Wiley & Sons Ltd, 1999) pg 23-25

enjoyed studying the arts and sciences of Europe as well as its great architectural heritage. Monticello, Mr. Jefferson's home located in Charlottesville, Virginia, was steeped highly in the neo-classicism of Palladio but more importantly it was Mr. Jefferson's private architectural test case. The house was modified continuously as Mr. Jefferson envisioned new things or felt compelled to try out new principles. One such case, and one that is important to this discussion is that of Mr. Jefferson's private study and bedroom. Thomas Jefferson had always been aware of the virtues of natural light and the wind and strove to incorporate these elements into his house. As a result all the windows on the main level were large and triple hung to allow daylight to infiltrate deeply into the house and to let the breezes to flow freely into and around the house. It should be noted that Monticello stood on the top of a hill and was continuously subject to the high level breezes that flowed around the Blue Ridge.

While most rooms in Monticello had direct access to the large triple sash windows there were a few interior spaces that lacked access to the light and air. This was the case in Mr. Jefferson's bedroom. Adjacent to his study, the bedroom relied on the light and air coming through the three large windows of the study. While the light was sufficient, Jefferson noted that the breezes never made it all the way to the back wall of the bedroom where he slept. To correct the situation Jefferson built a large 5-foot thick partition between the study and bedroom. Within this partition Jefferson built in his 6'-4" long bed as well as closets for his clothing. Jefferson had noted that if he placed the large opening for his built in bed in direct line with the windows that the breezes would flow through at a higher rate and reach the back part of the space. Mr. Jefferson also noted that by positioning the bed in this opening he could benefit from air flowing through the opening. Jefferson also cut in round apertures into the wall above the bed opening to allow even more fresh air and indirect daylight into the back of the space.[4] While this space may seem insignificant in the grand scheme of architecture it is a clear representation of the genius of a man and his understanding of natural ventilation principles.

**Figure 2-4: Jefferson's Bedroom (TJMF, 1996)**

### 2.1.4 The Impact Of Artificial Cooling

From the dawn of time through the 1870's mankind was dependant on the wind for cooling, and very few innovations had been developed, other than those methods previously mentioned. It was known that an opening correctly positioned in a wall would allow the wind in, but by 1870 mechanical fans and artificial cooling devices began to change the human perception of natural ventilation.

[4] Dumas Malone, Jefferson And His Time, vol. 6 (Boston: Little, Brown & Co., 1981)

Finally by 1900 the wonders of artificial cooling were being championed by refrigeration companies up and down the east coast of the United States. However up until this point these cooling devices were only being applied to factory uses, for cost and safety reasons. These systems not only took up large amounts of space, but the ammonia used could be deadly if released into the air and the expense of the upkeep of the system was quite substantial. It wasn't until 1902 when a young engineer from Cornell University revolutionized the industry and set the world on a path towards the wide spread use of conditioned air. His name was Willis Carrier and his name is now synonymous with the term "Air Conditioning" which some people believe he coined. While Carrier didn't invent the device he did perfect it and simplify it for use in commercial and residential spaces. For the next 100 years this would be the dominant approach to cooling and ventilation large commercial buildings. So that by the mid 1960's the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), had fully established itself as the authority on the heating, cooling and ventilation (HVAC) of structures. Through a series of standards written in conjunction with leaders in the HVAC industry ASHRAE became the single largest promoter of hermetically sealed, fully conditioned buildings. In fact to this day ASHRAE's two major standards on ventilation and occupant comfort, Standards 62 and 55, look unfavorably upon natural ventilation techniques. Thus by 1970 the use of natural ventilation was a complete non-entity with the exception of residential structures.

## 2.2 The Sustainability Movement

As a result of the oil embargo and oil crisis of the 1970's the United States, Europe and the rest of the world had to come to grips with the fact that energy resources were limited and had to be conserved. Large environmental movements for the conservation of energy formed and began to take hold in the world of architecture. Prior to this architecture had become static and uninventive but this was soon to change as well. Starting in the early 1970's a group of international architects began to question the building and design practices of the 50's and 60's. They began to question and explore ways to harness the natural elements to keep energy costs down and to remain true to the new environmentalist movement. The leaders early on were Richard Rogers and Norman Foster, two British architects, who began to study the benefits of daylighting and natural ventilation, and were intent on applying these benefits to modern architecture. During this time a young architect, Renzo Piano, an associate of Rogers, was also beginning to explore the ideas of environmentally conscious architecture on the scale of large buildings. While the early days of this movement in the 1970's were more about the experimentation and exploration of the concepts, by the early 1980's this level of thinking had developed into a crucial concept in modern architecture known as sustainability.

Sustainability is defined as the ability of a society, ecosystem or other ongoing system to continue functioning in the indefinite future, without being forced into decline through exhaustion or overloading of the key resources on which that system depends.[5] This movement was led by Foster and Rogers, however Renzo Piano, Nicholas Grimshaw, Sim Van de Ryn, William McDounagh and the firm of Kohn, Pederson Fox International were quick to become the new leaders in the design and application of sustainable architecture.

## 2.3 Norman Foster and the Commerzbanc

Sir Norman Foster's Commerzbanc is a design that some consider to be a perfect harmony between the aesthetic of architecture and sustainability. Designed in 1992 the 260-meter tower utilizes daylight and natural ventilation resulting in one of the most energy efficient buildings in Europe.[6] Foster enlisted the aid of the world renowned Ove Arup Engineers to help design the structural and ventilation systems for the tower.

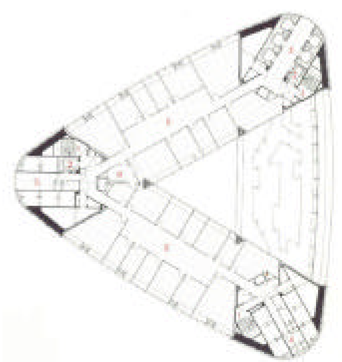


**Figure 2.5. Typical Floor Plate, Commerzbanc (Davies, 1997)**

Using the guidelines set by the client and the government, Foster set out to design a building where every office space not only had access to natural light, but also to natural ventilation and a view to the outside. To do this Foster designed a building triangular in footprint with a central stack that rose the entire height of the building. The building was then divided into twelve floor "villages" which were further subdivided. In each village there would be a four story internal atrium on one face, which would revolve and step up throughout the village connecting the facade with the central stack. Therefore each village would have 3 four-story atriums set 120 degrees apart from each other with every 4th floor being a continuous floor plate in the village. This spiral pattern revolved up the entire height of the building and created wedge shaped open spaces on each floor. While each atrium did have a glass façade on its exterior elevation the windows at each atrium were completely operable to allow air and

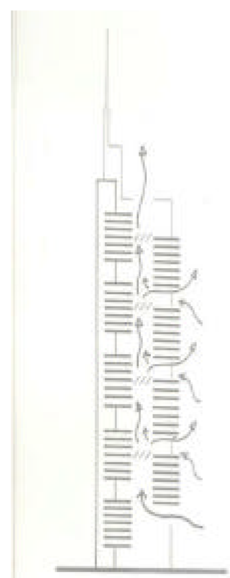


**Figure 2.6. Ventilation Scheme, Commerzbanc (Davies, 1997)**

[5] From the Architect's Handbook of Professional Practice, published by the American Institute of Architects, pg 651.
[6] Colin Davies, Commerzbank Frankfurt: Prototype for an Ecological High-Rise (Switzerland: Birkhauser, 1997) pg 13-19

light into the building. In fact the atriums were left totally unconditioned so that in the summer months they relied on surrounding breezes for cooling and the internal heat load of the building in the winter for warmth. To further solidify the connection between the outside environment and the atriums Foster dictated that trees, shrubs and plants accustomed to the climate of Frankfurt be planted in each atrium.

The two interior elevations of each atrium were composed of operable glass panels, which allowed in air and light. As fresh air passed into the atrium it would either filter into the office spaces or directly back to the central stack, which also provided natural light to the tower. Once the air from the atrium reached the stack it would rise through normal convection and buoyancy to the underside of the glass partitions set in the stack between every 12-story village and vent out. Cross ventilation was achieved by using a double envelope system on all exterior and interior facades. Air brought in through cross ventilation would then flow to the central stack where the air could either travel upwards or continue through the building to the other facades and out.[7]

## 2.4 Renzo Piano and the Tjibaou Center

**Figure 2.7. J. M. Tjibaou Cultural Center, New Caledonia (Gili, 1998)**

Another significant naturally ventilated modern building is Renzo Piano's J.M. Tjibaou Cultural Center in New Caledonia deep in the South Pacific. In this project Piano was challenged with incorporating cutting edge technology with the architectural heritage of a primitive culture. New Caledonia is a cluster of small islands well off the east coast of New Zealand with deeply rooted Polynesian heritage. For the most part the inhabitants held onto their cultural and architectural heritage, where the primary buildings were primitive huts and homes made from indigenous trees and plants. In terms of weather conditions the islands were in a hot, humid tropical climate with a prolonged rainy season, but did benefit from brisk ocean breezes for cooling needs. These were the concerns that Renzo Piano had to contend with while designing the Tjibaou Center in Noumea, one of the large towns in New Caledonia.[8]

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[7] Davies pg 29-45, pg 193-195
[8] Renzo Piano, Logbook (Genoa: Monacelli Press, 1997) pg 174-183

The resulting design was a masterful conglomeration of the high-tech engineered approach Piano had used before with an aesthetic reminiscent of the indigenous architecture of the area. The front of the cultural center was divided into 10 “houses” or pods, which were round in nature to reflect the local housing. Each of the divisions varied in diameter and height and were made of long “fingers” of iroko wood that were connected together by smaller lattice elements also of wood. This screen was infact the front screen of a very elaborate double envelope system. Behind each of the wooden screens were a series of louvers and steel connectors that attached to the main shell of the building. The main building was made predominantly of wood, steel and glass, with the façade behind the wood screen being entirely of steel and glass. Within this second screen there were a series of operable louvers at the floor level and at the apex of the sloping ceiling. Along the backside of the center was another series of windows with operable louvers as well, that could be controlled in tandem with the louvers of the double envelope façade depending on the wind conditions.

As Piano developed the project it was determined that the double envelope in conjunction with the back window wall could operate together in approximately 5 different configurations. With the wind coming off the ocean into the double screen the floor level louvers on the inner screen would be open to let air pass into the space. Likewise the upper level louvers by the ceiling would be opened as well. The intention was that, as air passed through the wooden fingers above the roofline it would induce the stack effect in the cavity between the two screens.[9] By doing this air would flow into the building through the low end and convectively loop back and up the sloped ceiling to the high louvers and exhaust out and up into the envelope chamber. Piano also designed the system to work if the wind direction changed and was blowing against the backside of the center. Again fresh air would pass through open louvers and again move convectively through the space towards the double envelope. Since the double envelope’s design above the roofline was fairly straightforward the stack effect would also take effect when the wind was blowing in the opposite direction and would extract the air much like in the normal configuration.

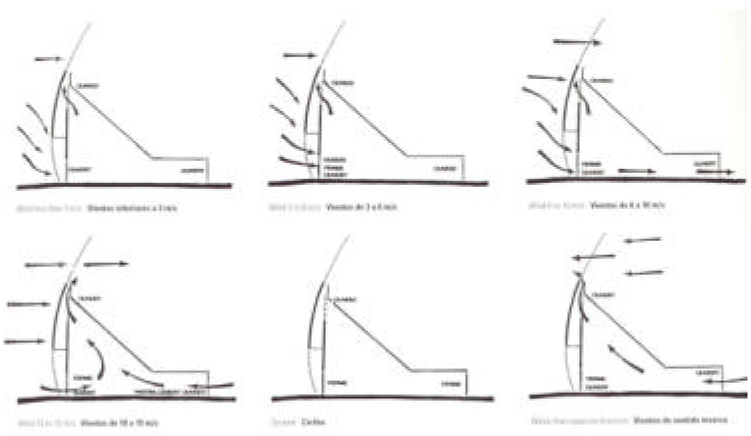

**Figure 2.8. Ventilation Diagram for Tijbaou Center (Gili, 1998)**

[9] Gustavo Gili, ed., Renzo Piano, Sustainable Architectures (Barcelona: Gingko Press, 1998) pg 4-15, pg 34-39

## 2.5 Kohn, Pedersen, Fox

In 1986 after the successful design of the U.S. Embassy at Nicosia, Cyprus Kohn Pedersen Fox established an international office in London, England. KPF International was placed under the direction of Lee Palisano and David Leventhal, and set to work to broaden the firm's presence in the European market. Up to this time a great deal of the buildings KPF designed were cooled and lighted by artificial means however influences from the new architecture in Europe did begin to influence the design philosophy of the firm. While the firm did strive to incorporate daylighting when ever possible it wasn't used as a wholesale design element until the mid 1990's with the Oxford Library of American Studies in 1998. Another building was Thames Court in London (1998), a 5-story office building with a large central atrium that utilized a louver system for daylighting and used a progression of spaces that led to the atrium space. The third project was the Cypriot House of Representatives (1998), which incorporated a large atrium space with double envelope walls. The lessons from these three buildings paved the way for the firm's next project, The World Trade Center in Zuid-Amsterdam. [10]

## 2.6 The World Trade Center, Amsterdam

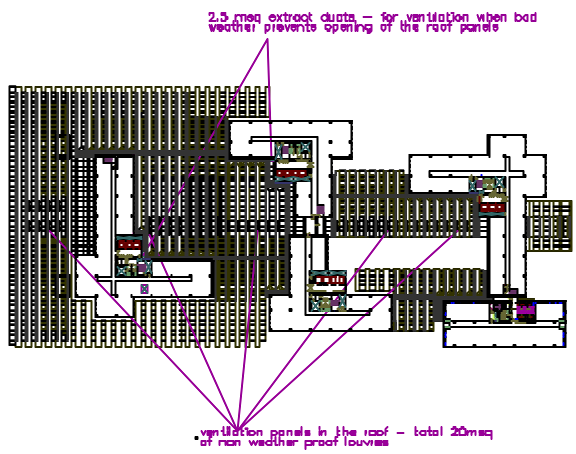


**Figure 2.9. WTC Roof Plan (KPFI)**

In the mid-1990's Western Europe was in the midst of a huge economic boom. Amsterdam in particular was seeing resurgence as a financial and business capital of the newly created European Union and was committed to bringing in new international businesses to the city. A proposal was laid out for the renovation and expansion of the World Trade Center complex in the Zuidplien region of the city. The refurbished complex was to house these new businesses as well as retail shops. KPFI won the design competition and began to develop a series of atriums around the existing multi towered World Trade Center (WTC) Complex on the southern edge of Amsterdam.[11] The first phase of the WTC, and the focus of this study, is a multi-million square foot complex comprised of five separate towers, four of which exist and a fifth designed by KPF, connected by interstitial atrium spaces. The towers, aligned on

[10] Kohn Pederson Fox, Firm Description & Philosophy: Born In The USA
[11] For graphic information on the WTC please refer to the building keys on pages XIII-XVI at the beginning of this text.

an east-west axis and range from 12 to 18 stories in height, while the atrium spaces range from 4 stories on the east side to 8 stories in height on the western face of the complex.

From the initial phase of design KPF enlisted the aid of Battle-McCarthy Engineers, a worldwide leader in natural ventilation, to develop a system for passively ventilating the atrium spaces. KPF and Battle-McCarthy designed a saw tooth roof profile to create turbulence and negative pressure zones along the roof edge. By creating these negative zones of pressure the operable louvers will act as exhaust ports for the positively pressurized atrium spaces. In order to bring air into the atriums KPF devised a series of intake louvers situated above the entry doors on the north and south atrium walls. These louvers are integrated into the atrium facades and are situated under deep overhangs provided by the roof panels, which force air around the complex in towards the intake louvers at a higher velocity.

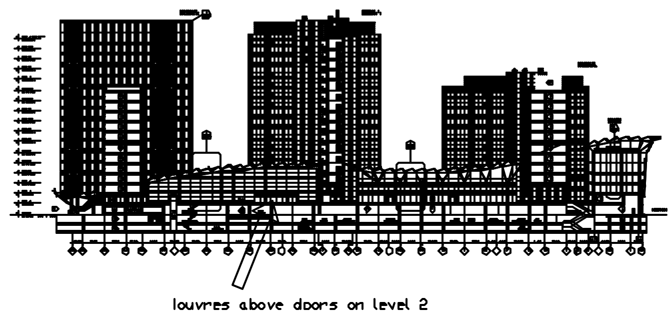


**Figure 2-10: WTC Cross Section (KPFI)**

This of course is all speculative at the moment. At the time of this writing the complex has been under construction for just under a year and is quite far from completion. While KPFI and Battle-McCarthy have run wind tunnel tests and computational fluid dynamic tests on scale models it is still uncertain whether the proposed system will work as expected. It is as this point where the grounds for this investigation come in. The driving principles behind this thesis are to first understand the concepts and methods being undertaken by KPFI on this project and then to understand the applicability to large structures similar in size and scope. To date at completion the World Trade Center will be the largest naturally ventilated space in the world. While a full analysis of this complex would be too lengthy to complete this study focuses directly on the application of the roof system and how it affects the movement of air within the atrium spaces. By placing this limitation on the study a number of crucial questions can begin to be answered in regards to KPFI's design. First and foremost: Does the roofline as KPFI has proposed really behave as stated or is

**Figure 2-11: Study Model of WTC (KPFI)**

the roof profile more or less an abstract representation of a fundamental concept? In other words is the roof merely a showpiece. Secondly, if the roof is in fact a fully functioning system how does it react to varying wind and directional conditions? And finally, is the roof system as designed set at it optimum configuration or are there alternative methods and better ways to passively extract the air out of the atriums? The following body of work as well as the preceding pages represent close to a year's investigation into the subject matter of the science of natural ventilation and it's application to large structures. The preceding paragraphs were intended to be a brief look into the history of natural ventilation, just as much as the following pages intend to be a detailed look at the physics behind ventilation and the specifics of one building through the use of scale modeling and wind tunnel analysis.

## Chapter 3: The Science of Natural Ventilation

*2nd Law of Thermodynamics: Among all the allowed states of a system with given values of energy one and only one is a stable equilibrium state. Such a state can be reached from any other allowed state of the same energy and leave no effects on the environment.*[1]

### 3.1 General Concepts of Pressure and Stack Driven Systems

The Second Law of Thermodynamics simply states that an energy source will seek a point of equilibrium with another similar energy form. While this may seem vague the 2nd Law governs the behavior of energy in the world, as we know it. This law also establishes the basic principles of fluid dynamics and how the atmosphere of the earth acts. As seen on the Weather Channel the earth's atmosphere is a tumultuous activity of weather but it is in fact in a state of equilibrium. The weather, which we witness, is the resulting force of the atmosphere trying to obtain a balance of pressure. In the simplest terms the atmosphere is comprised of a series of air streams, which revolve around the earth. Most follow a West to East pattern, but these streams are affected by air pressure and temperature variations across the globe. It is these variations in pressure and temperature that force these air systems to move around the globe in search of a static state.

It is this attempt to reach equilibrium that creates the weather, which brings us rain, snow, hurricanes, tornados and most importantly wind. Generally speaking weather acts as such around the globe. Around the equatorial region the atmosphere is heated by the intense energy of the sun and proceeds to evaporate water from the oceans. As the air gets hotter it picks up more moisture and becomes less dense. These warm low-pressure systems are then moved around the globe by pre-existing upper level currents and by localized ocean currents (the Trade Winds and the Gulf Stream for example). Concurrently air systems of high pressure and dense cold air are generated in the arctic regions and are also moved around the earth by these upper level systems. Due to the principles of thermodynamics and physics these warm air systems generally move faster than the colder systems, which leads the two systems to sooner or later converge. At the point of convergence the 2nd Law of Thermodynamics will take hold again and the higher-pressure system will begin to push the low-pressure system out of the way as it releases excess energy. In meteorological terms the convergence of a low-pressure system and a high-pressure system is called a "Front". Along this weather front colder, denser air will push under the hotter less dense air. At some point the cold air will cause the moisture contained in the warm air to condense, fall out of phase and drop to the earth as precipitation. The temperature of the cold air will determine the type of

[1] "Thermodynamic, Principles of", Encyclopedia Britannica, 1982 Ed.

precipitation that reaches the earth. In conjunction with the moisture convergence the air from the high system will forcefully move to the low system at a noticeable velocity. This is in effect what we called wind and generally speaking the velocity of wind is higher at a weather front than in other areas of the weather system. However this is not to say that wind only occurs at a weather front. In fact that is far from the case. Wind will be generated at any place where there is a pressure variation, even within an individual weather system. The velocity and intensity of the wind is contingent on the pressure variation between the two weather cells and the direction of the wind is contingent on the orientation of the high pressure gradient in relation to the low pressure cell. Natural Ventilation is effectively the harnessing of local wind pressure or stack driven pressure changes to create a desired cooling effect.

While for the most part wind is studied on a large geographic scale, the effects of wind currents can play major roles in the performance of any built structure. For local conditions wind is affected by the terrain and obstructions in the area. In areas that are relatively flat and open the wind speed at 33 feet is generally only 60% of the wind's full potential.[1] Likewise in a suburban condition this number drops to 35% and in urban conditions drops further to 21%. These values can be generated from a variety of equations that make up a chart called a mean wind speed profile. While these values are general they do exhibit the fact that a pressure gradient does exist for all situations, and thus it can be assumed that a single building will experience the same type of pressure gradient. In the simplest of terms as air moves across a specified area the higher off the ground plane the current is the closer it will be to reaching it's full potential energy. Thus the higher an obstacle the higher the air must travel to reach full speed.

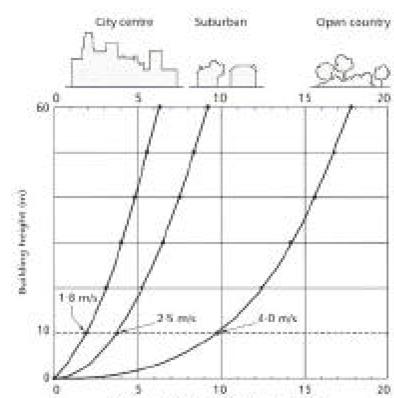


**Figure 3.1. Mean Wind Pressure Gradient (CIBSE, 1997)**

## 3.2 Wind Driven Strategies

In the most basic of terms there are two critical methods for passively moving air, wind-induced and stack-induced pressurization. For wind induced pressurization there are two effects that are important, the Bernoulli effect and the Venturi effect. There are also a series of wind-induced strategies that rely on pressure changes at the inlet and outlet locations of a structure. These are simply known as wind shadows, single sided ventilation and cross ventilation.

[1] ASHRAE states that 33' is the general placement height for meteorological equipment at most airports, which are usual the largest areas of flat and open land.

While each principle behaves in a slightly different manor they are all driven by local pressure differences that are generated by local weather conditions, building geometries as well as localized pressure gradients.

### 3.2.1 Bernoulli Effect

The Bernoulli effect relies on the change in velocity and pressure of air over two surfaces of different length and profile in order to move air. To best understand this effect imagine an airplane wing. Typically the underside of an airplane wing is relatively flat while the topside is curved. The leading edge of the wing is rounded to allow the air to split off and the back edge of the wing is tapered to form a slipstream. As the air reaches the leading edge of the wing it is split by the rounded profile. The air that passes underneath the wing loses some velocity and builds in pressure. However the air flowing over the longer "curved" part of the wind speeds due to less resistance and decreases in pressure. At the slipstream on the trailing edge the two streams of air converge with the slower air pushing up from below into the top air stream. This is the basic principle of lift and it is what keeps airplanes aloft. This principle also can create enough of a pressure difference to extract air out of a space. If the extraction point for a space is located beneath the wing the lower air stream will pull the air through the port as it converges and lifts into the upper air stream. With this being the case the Bernoulli effect is often represented architecturally as a rooftop element along a series of exhaust ports or as a cap over an extraction shaft.

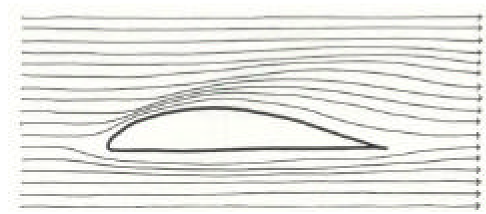

**Figure 3.2. Principle of the Bernoulli Effect (Moore, 1993)**

When calculating the Bernoulli effect it is best to utilize four different formulas for the four primary locations on the wing.[2]

1) Ahead of the wing the velocity of the wind is calculated as a function of pressure and energy as represented by **equation 3.1.**

$$(r_{\mu} + r/2 * w_{\mu} = C) \qquad \textbf{EQ 3.1}$$

2) The point where the air stream splits off is called the point of stagnation, or position 1 is represented by **equation 3.2.**

$$r_{1} = (r_{\mu} + r/2 * w^{2}_{\mu}). \qquad \textbf{EQ 3.2}$$

[2] Klaus Daniels, The Technology of Ecological Building (Birkhauser, 1997) pg 49, fig 39

**3)** As the air decelerates along the bottom edge of the wing at position 2 the pressure drops and is calculated using **equation 3.3.**

$$\mathbf{r_2 = (r_1 - r/2 * w^2_2)} \qquad \textbf{EQ 3.3}$$

**4)** While on the acceleration along the top edge or position 3 is calculated using **equation 3.4.**

$$\mathbf{r_3 = (r_1 - r/2 * w^2_2)} \qquad \textbf{EQ 3.4}$$

Where:

**r** = Pressure
**w** = work
**C** = some constant velocity
**μ** = First position in the stream.

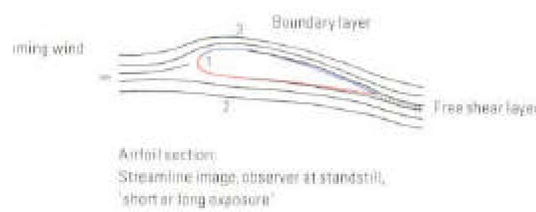


**Figure 3.3. The Bernoulli Wing (Daniels 1996)**

While these equations are somewhat daunting they do if applied show that there is a pressure change and velocity change at each point and that each point in the sequence has a resultant connection with the point prior to it. Nevertheless these functions can be easily traced back to a fundamental equation, **equation 3.5.**

$$\mathbf{(DE = W+Q)} \qquad \textbf{EQ 3.5}$$

Where:

**DE** = change in energy
**W** = work
**Q** = heat energy

Which says that the change in energy is a result of work and any absorbed heat from said work. In terms of the application of the Bernoulli effect this represents the change in pressure as velocity and surface resistance vary.

### 3.2.2 Venturi Effect

The Venturi effect is in essence the principle of pushing air through a smooth constricted passageway. By definition the principle states that as a given volume of air moves through a given area it will maintain a certain velocity. If the same volume of air is pushed through a

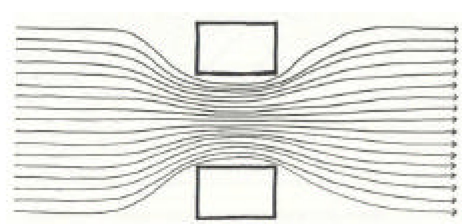

**Figure 3.4. The Venturi Effect (Moore 1993)**

smaller area the velocity will proportionally increase as the driving pressure attempts to push the air through. For example imagine a typical garden hose. When turned on the hose will force a given amount of water at a calculated speed through the nozzle. Now if one were to place their thumb so that it covered a part of the aperture the velocity of the exiting water would increase as the hose attempts to pump out the same amount of water through a smaller opening. This principle when applied to fluid dynamics has it that air constricted by an obstruction will flow through an opening at a faster rate. This application is easily seen in Thomas Jefferson's bedroom at Monticello and in the traditional "dogtrot"[3] homes of the Southern United States. In the dogtrot house the building was divided into two blocks separated by an open corridor beneath a deep porch. The porch would funnel the air towards the building and the corridor or dogtrot would increase the wind speed. Windows and doors placed along the corridor would then receive air as the wind attempted to bleed off the pressure and speed it had picked up. This method proved to be very effective in the hot, humid climate of the south. While the Venturi effect is seen in modern architecture as a way to bring air into a space it is also used widely as a means for extraction. Much like the Bernoulli "wing" a Venturi "cap" or "disc" can be placed directly above an exhaust port. By creating a constricted space directly over the exhaust port the velocity of the air is increased. This creates local eddy currents of negative pressure at the exhausts and pulls the air out and into the fast moving stream under the cap. However if the cap is placed too close to the extraction points the element could constrict the air flow between the cap and roof to a point where the on coming winds would stack up at the cap thus creating a dead zone without pressure of velocity. In a sense if the constriction is too much a Venturi "cap" can become a windbreak.

### 3.2.3 Inlet And Outlet Strategies

Imagine a small wall 5 feet tall standing in the middle of an open field with a stiff breeze blowing towards and over the wall. If pressure readings were taken it would be noticed that the air pressure at the windward face of the wall would be considerably higher than the air pressure recorded in the open field. Likewise the pressure reading on the leeward (back) side of the wall would be considerably lower than the open field reading and the windward reading? Why? In a word, resistance. As the wind blows on the wall the wall gives resistance to the air and forces the air to build up at the wall. The air pressure will be higher the lower on the wall a reading is made. In the same vein the wind at the top of the wall will find some resistance, but will nonetheless be deflected slightly creating a slipstream on the backside of the wall. This slipstream creates a zone of negative pressure directly behind the wall as the air in that area is pulled out by the faster moving slipstream. This simple principle is called a "Wind break" and is often used as an architectural element for deadening the effect of the wind on a given area. A general rule of thumb for windbreaks is that the velocity of the wind on

[3] Fuller Moore, Environmental Control Systems (McGraw-Hill 1993) pg 188-194

the leeward side will be affected for a distance up to five times the height of the obstruction.[4] This distance is often known as the wind shadow, or the area on the leeward side of an obstruction in which the wind velocity is significantly reduced. Also the windbreak can lower the velocity of the oncoming breeze by as much as 50% depending on orientation. Therefore in the example of the 5-foot wall, a wind shadow of 25 feet would be created and if the wind were blowing at 10 Mph, it could be cut down to approximately 5 mph[5]. The concept of the windbreak is essentially the catalyst for almost every natural ventilation application, as each one relies on a pressure change from one face to another.

The first and simplest method of natural ventilation is known as Single Sided Ventilation. In this application a space is ventilated from one and only one side. In most instances this is a simple window, which allows air to flow into the space, is placed on a wall and uses localized turbulence generated on the face of the wall to bring in air. While this method is generally effective the velocity of the incoming air is often very low and has a limited range of penetration into the space.

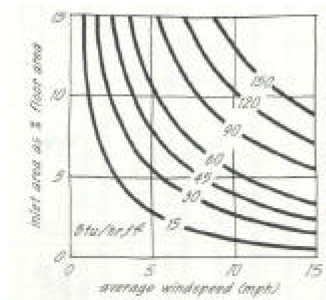


**Figure 3.5. Inlet Area vs. Wind Speed (Moore 1993)**

A slight variation of the single sided ventilation system is the double opening method. In this variation a single wall has openings at two heights, generally one high and one low. Air is brought in through the lower opening and through the stack effect is drawn out of the higher opening. The added benefit here is that the air can move slightly further into the space, but is still limited by the low velocity. The general rules that govern single sided ventilation are such. For a single opening system the penetration depth of the incoming air will be two times the height from floor to ceiling (2:1 ratio). For a double opening on a single wall the ratio moves slightly higher to a 2.5:1 ratio. Therefore a room with a ceiling height of eight feet (8') can expect a ventilation depth of up to 16'. However this is totally dependant on the pressure acting on the surface of the outer wall due to the wind velocity. The relationship in this instance is a square function; as velocity increases the resulting air pressure increases as well.[6] Which is based on the equation **3.6.**

$$r_v = r_a * U^2_h / 2g \qquad \text{EQ 3.6}$$

[4] Moore pg 188-190
[5] Example of wind shadow loosely based on principles discussed in Daniels' The Technology of Ecological Building and Moore's Environmental Control Systems book.
[6] CIBSE 3.3.1

Where:

**U** = wind speed
**r** = Pressure
**g** = acceleration due to gravity

Cross ventilation uses the ability of the wind to move through a space from one opening to another opening. In the simplest variation there would be two openings set directly opposite of one another to allow the breeze to carry directly through the space. Cross ventilation works under a velocity driven principle where the velocity of the air at the inlet is directly related to a change in air pressure. In the velocity driven mode wind blowing in through one opening has enough velocity to push it through the space and on out through the other opening. While this is effective it does require a substantial sustained velocity. Thus most cross ventilation strategies employ the pressure driven method. As air hits the side of the building pressure builds up and forces the air through the opening as a higher velocity. Concurrently the wind is blowing around the building edges and creates a slipstream behind the opposing wind. This in effect positively pressurizes the front window and places a pocket of negative pressure directly behind the leeward window. This difference in pressure will cause the air within the space to push towards the negative pressure zone. Mathematically the overall effectiveness of cross ventilation limits the width of a building or space. Much like the single sided ventilation strategies, cross ventilation can effectively work in spaces up to five times as deep as the floor to ceiling height (5:1). The effective cooling ability of cross ventilation is also governed as a square function relationship between the percentage of inlet area to floor area against the average wind speed. The relation between each of these variables determines the amount of Btu/hr.ft$^2$ that the air can cool. Logically the higher the wind speed and the higher the inlet area the better the cooling effect. Nevertheless cross ventilation and the principles that govern it also govern the following methods of natural ventilation

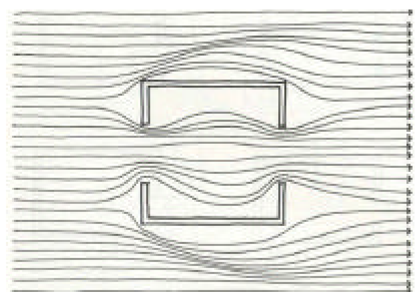

**Figure 3.6. Cross Ventilation Diagram (Moore, 1993)**

### 3.3 The Stack Effect

The stack effect is closely tied to cross ventilation in that it uses an inlet source as well as an exhaust. However the stack effect utilizes a stack or chimney as the exhausting mechanism. Generally the stack effect is governed by the same 5:1 ratio as cross ventilation but can go beyond that

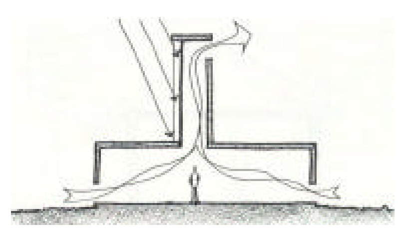

**Figure 3.7. Simple Stack Effect (Moore, 1993)**

ratio if the draw on the exhaust system is higher. As air is brought into the space due to a pressure build up on the façade it moves into the depths of the space. At some point this air loses velocity and is then driven towards the exhaust stack through a difference in pressure. Once the air is in the exhaust stack it then moves up the stack and out the top exhaust port by one of two methods.[7] The stack effect can also be represented mathematically by the **equation 3.7**

$$PD = 0.00027 \times Feet_{NZH} \times (t_i - t_o) \quad \text{EQ 3.7}$$

Where

**PD** = pressure difference due to stack effect in inched of water (in wc)
**0.00027** = typical estimate of stack effect in inches of water/ft from NZH/deg F
**$Feet_{NZH}$** = vertical distance from Neutral Zone Height in feet
**$t_i$** = inside air temperature in degrees F
**$t_o$** = outside temperature in degrees F

It should be noted here that the stack effect can work for single height and multi story spaces, however as a building rises in height more inlet area is required as the building rises off of ground level. This is partially due to a simple principle in fluid dynamics that states at some point on the face of a building the stack-induced pressure will find a balance point.

### 3.3.1 Neutral Zone Height

This point is known as the neutral zone height (NZH)[8]. The NZH is the point on a building when there is no pressure gradient across the façade. Also at this location the positive pressure build-up at the bottom of the structure gives way to the negative pressure zone created by the slipstream at the roof edge. Below the NZH the pressure is higher than the normal air pressure at a given velocity. Above the NZH the air pressure gradually gets lower as it moves to the top of the

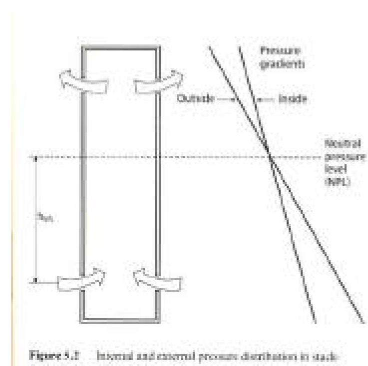


**Figure 3.8. Neutral Zone Height (NZH) (CIBSE, 1997)**

[7] W. Bobenhausen, Simplified Design of HVAC Systems (John Wiley & Sons Inc., 1994) pg 103
[8] NZH is also sometimes referred to as the NPL or Neutral Pressure Level. The nomenclature for this concept varies from text to text.

building, thus more inlets are needed to bring in the same amount of air as on the lower levels.[9] Nevertheless the stack effect works on two principles. The first and simplest principle is that of a general pressure difference between the air in the stack and the air flowing over the exhaust port at the top of the tower, due to the principles that govern the neutral zone height. The air in the stack is almost always under positive pressure as the extracted air builds up within. Thus by placing the stack in a known area of negative pressure the stack will naturally purge itself to the low pressure side and will keep the column of air in the chimney constantly moving. The rate of extraction would then be dependent on the pressure gradient between the outside and the interior of the stack as well as by any wind velocity over the stack. An example of this is the malqaf towers of the Middle East.

### 3.3.2 Thermal Buoyancy

The second and more complex variation of the stack effect utilizes something known as thermo siphoning and thermal buoyancy. Recalling the beginning of this chapter thermal buoyancy is the principle that states that warmer air is physically less dense than colder air and will rise above any air that is denser. Thermal buoyancy is also known as convection where cold air gradually heats up and moves through a space to its highest point as it picks up heat. Thermo siphoning is the application of thermal buoyancy to a fluid system (air, water ect.). In this application the air is drawn to the extraction chimney and gradually rises through the stack as it gains heat. More often than not the chimneys are constructed of materials with a high level of heat transmission, so that the chimney heats the air. These systems are called Solar Chimneys. The quicker the air picks up heat the faster it will rise through the stack. Likewise if the air flowing over the exhaust port is colder than the stack air, the air in the chimney will move faster in an attempt to dump it's heat off in the colder air.

**Figure 3.9. Florida A&M School of Architecture (Moore, 1993)**

This method of using a solar chimney is best seen at the School of Architecture at Florida A&M University. In this academic building by Clements, Rumpet Associates air is brought in through classroom windows and laboratory windows by means of cross ventilation and single sided ventilation principles. Exhaust ports located on the far wall, which is formed by the classroom walls and a glass façade are then used to

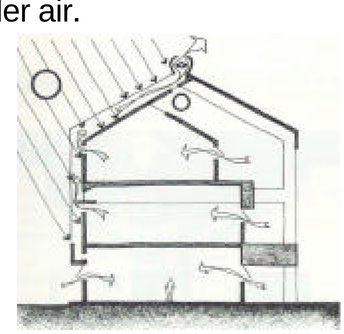

**Figure 3-10: Vent Diagram for Florida A&M (Moore, 1993)**

[9] Klaus Daniels pg 74-75; ASHRAE Fundamentals v.1993, 14.1-14.2

pull the air through the classrooms and into the cavity. This glass wall heats the air up in the cavity and through thermal buoyancy and the stack effect moves the air towards the exhaust port at the ridge of the roof where local air currents extract the heated air.

The stack effect is another application of the 2nd Law of Thermodynamics. Each system can work in conjunction with the other and in most cases the stack effect uses both methods for extraction. A prime example of this hybrid system would be Sir Norman Foster's Commerzbank project, which was discussed in Chapter 1. Mathematically the stack effect is driven by the pressure gradient over the height of the building. As mentioned prior, any part of a building above the neutral zone height (NZH) is more apt to exhaust air then bring air into the space. The effectiveness of the stack effect in terms of the volume of air it can move is almost solely driven by the height of the stack's exhaust port in relation to the NZH datum. Using a simple formula in **equation 3.8.**

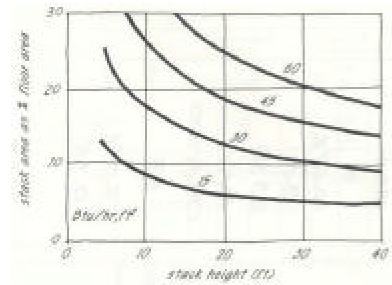


**Figure 3-11: Inlet Area vs. Stack Height (Moore, 1993)**

$$DR = (R_{out} - R_{in}) * g * (h - h_{npl}) \qquad \textbf{EQ 3.8}$$

Where:

$R_{out}$ = the air pressure outside in ($kg/m^3$)

$R_{in}$ = the air pressure inside in ($kg/m^3$)

**g** = acceleration due to gravity in ($m/s^2$)

**h** = the overall height at the exhaust port in (m)

$h_{npl}$ = the height of the neutral pressure line (m)

The overall ability for an extraction stack can be calculated. An even simpler function of the overall ability of the stack effect can be seen as an inverse square function between stack height (ft) and the percentage of the stack area on each floor. In this algebraic function the resultant between these two variables will regulate the amount of heat in BTU/hr.sqft that the stack can extract.

## Chapter 4: Research Procedures and Methods

When studying airflow and localized wind patterns for buildings there are three common methods of evaluation: in-situ monitoring, scale model testing using a wind tunnel and computational fluid dynamics. Of the three test methods the most accurate is the in-situ monitoring. In these tests as-built systems such as wall assemblies, wind scoops, double envelope windows and a variety of other elements are observed for actual weather conditions. Instruments such as, airflow transducers, pressure sensors and wind monitors are then attached to the system or building. While in-situ monitoring is far and away the most reliable test method the procedure does require a substantial amount of time and cooperation of building occupants as well as a large number of sensors and data recorders and often does not provide enough information about the macro environment around the building. However the macro environment of a building site can be tested using the two other common testing methods. The first of these two methods uses the same principles of in-situ monitoring, except at a smaller scale. For this approach scale model test are conducted in wind tunnel facilities, for either the overall ventilation strategies of a building or the performance of one element or façade. Scale model testing is probably the most common method and while it does generally produce results similar to real world conditions the fact that a scale factor is involved does potentially limit the reliability of the test results. Likewise wind scale model testing cannot account for thermal buoyancy thus results from model testing must be seen as a minimum value. While wind speeds and airflow measurements cannot be scaled, the effect of a 4 mph wind on a small model is the same as on a real structure. Thus a small variance in a dimension on the model can translate into a large dimensional discrepancy at a real world condition. Nevertheless scale model wind tunnel tests are extremely useful in preliminary test design.

### 4.1 Computation Fluid Dynamics

The third method used in natural ventilation research is computational fluid dynamics, or **CFD** analysis. CFD analysis is the use of a computer-modeling program that allows the building's geometry to be input and then run through a series of tests. CFD simulations typically use a finite-volume mesh to define the spatial geometry. The conservation of energy, mass, momentum and species equations are simultaneously solved to predict the room airflow. In doing CFD test apertures, exhaust ports, and any other critical building elements are tested against simulated wind speeds, air pressures and temperature gradients. This last fact is perhaps the one function that separates CFD analysis from the other two methods. While wind speeds and air pressure can be accounted for in full-scale and scale model tests it is very difficult to determine how the building will react to changes in the air temperature. However FCD analysis can test for changes in air temperature and how this change affects a structures performance. While CFD analysis does have this advantage, as well as a high level of accuracy it does have it's drawbacks, which prevent its widespread use. First and foremost CDF programs such as FLUENT are extremely complex and input for large systems or buildings can be very time consuming. Likewise there is a continuing debate over whether to use the RaNS or LES equation for generating the model. Secondly for complex geometries with small grid spacing these programs can potentially take extended periods of time to run the simulations. Similarly a preferred mesh size for the grid and a suitable time step for running the simulation have yet to be agreed upon by the industry. While it might take a week to build and test a scale model it may take twice as long to input the computer model and run the necessary simulations. However the largest potential drawback in CFD analysis is the cost, currently the site license for FLUENT ranges from $2,000 to $10,000 per year. However the biggest disadvantage of CFD analysis currently is the lack of any validation for CFD programs in relation to actual building studies. As of now all CFD studies have been predominantly theoretical. Nonetheless these three methods, in-situ, scale model with wind tunnel and CFD all have their advantages and disadvantages.

## 4.2 Introduction to the WTC

In the spring of 1999 KPFI supplied Virginia Tech with a series of digital flies that contained plans, sections, elevations and 3-D models for the World Trade Center. Once these materials were received a formal investigation into the overall program, building form, plan layout and general spatial qualities of the complex was undertaken. The following is a brief description of the basic layout, as it will appear once KPFI's proposed additions have been completed.[1]

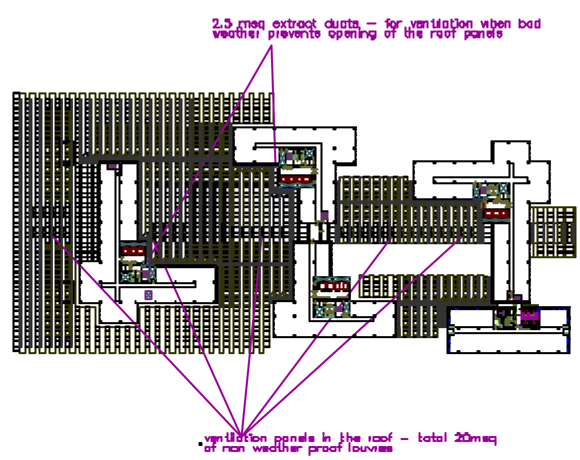


Figure 4.1. WTC Roof Plan (KPFI, 1999)

Formal entry into the complex is from the west and south[2], while the less formal entry into the complex is off the large pedestrian plaza situated on the north side. The west atrium roof rises 8 stories and pushes in towards tower "A". There are two office blocks situated on piloti that are completely encompassed by the west atrium roof and walls. Visitors are forced to walk under these volumes in order to reach a bank of escalators and elevators directly beneath the main mass of tower "A". At this point the visitor either enters the

[1] For additional information on the WTC please refer to the Building Keys in the beginning of this text on pages XIII-XVI.

[2] The south side of the complex is adjacent to the Zuid Rail station, one of the main stops on the rail line from Schinpol International Airport to the Central Station in Downtown Amsterdam.

tower or proceeds up the escalator to the main floor and on into the middle atrium. The middle atrium spans between tower “A” and towers “B&C” and runs from the 6th story on the west side (“A” side) to 5 stories in height at the middle towers.

The atrium walls are constructed of a steel frame and glass system, while the tower are traditional curtain wall system structures. Tower “A” is 13 stories tall while Towers “B&C”, which are the two main buildings in the complex, are twin 18 story structures at the center of the complex. While in plan Towers “B&C” appear to be one solid unit they are actually separate units connected by an enclosed breezeway at every level. This breezeway is situated on the central spine of the entire complex upon which all the towers and atriums align. Between the east faces of towers “B&C” and the west façade of Tower “D” sits the smaller East atrium. The east atrium is four stories tall and has a smaller profile than the main atrium of the complex. An open-air canopy on the southern side of the East atrium defines the southern area of the complex, while also providing a shade garden on the south side. Closing off the eastern end of the complex are towers “D” and “E”. Tower “D” is a mirror copy of tower “A”, while Tower “E” is to be the new tower designed by KPFI. Tower “E” is a simple, slender 18-story tower with a rectangular footprint and is to be located on the southeast corner of the complex.

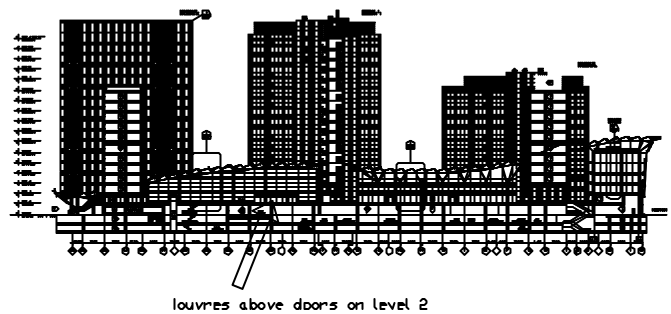


**Figure 4.2. Section Through WTC (KPFI)**

## 4.3 Test Procedure

To test and understand the ventilation principles discussed in Chapter 3 in regards to the WTC a logical, systematic method of experimentation was developed. Due to it’s availability it was decided to perform the analysis using the wind tunnel on the Virginia Tech campus. Two issues were of primary concern. First, what would be the airflow conditions on and around the building as a result of dynamic wind speed and directions? And second, what would be the resulting natural ventilation conditions inside each of the atriums? For this two series of tests were performed, one using a 1:250 scale model and the other using a 1:64 scale model. The 1:250 model provided data for airflow patterns in and around the building. The 1:64 scale model was more detailed and included a more accurate representation of the atrium roof openings and fins. Both models were constructed of chipboard and plexiglass. Both qualitative (visualization) and quantitative analyses were performed. Tests were performed for each model for a range of wind speeds and directions.

## 4.4 1:250 Site Model Test Procedure

A 1:250 scale model of the WTC was constructed of chipboard and plexiglass. 1:250 was selected as the largest scale model that could be built that could be transported and placed in the wind tunnel. The model included five high-rise towers and three separate atriums each with side inlets above the entries and outlets at the ridge of the roof spine (see **Figure 4.2**). TSI omni-directional airflow transducers, model TSI #8475, were placed at the atrium inlet, roof outlet and near the geometric center of the atrium. Because only three transducers were available separate tests were performed for each of the three atriums. For each series of atrium tests wind direction from eight directions (N, NE, E, SE….) was simulated at each of three different wind speeds (4,8 and 12 mph). For statistical reliability each test was repeated three times. Each test was run for five minutes with readings being taken at five-second intervals.

**Figure 4.3. 1:250 Model of WTC**

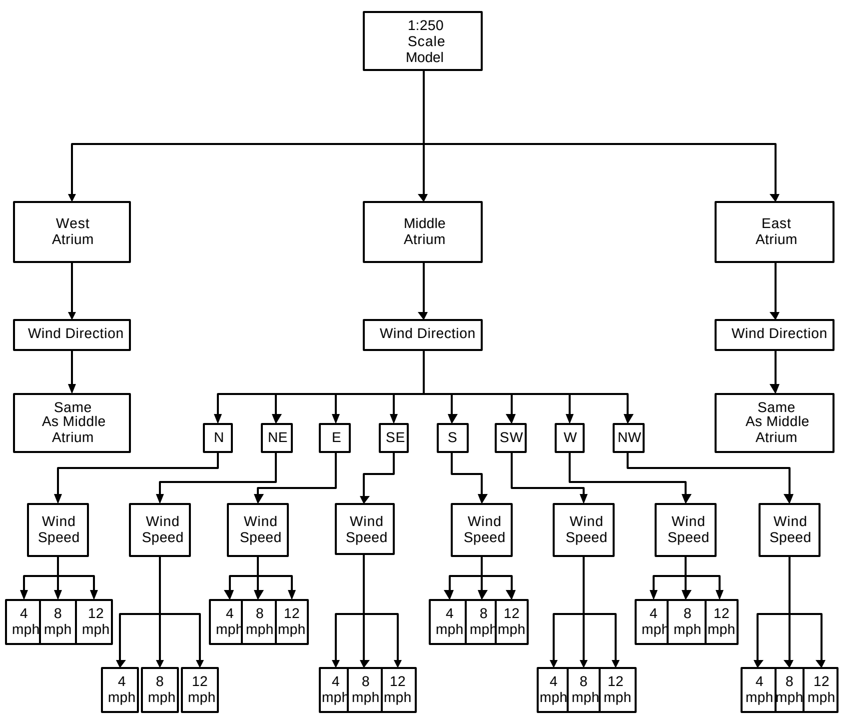


**Figure 4.4. Test matrix for 1:250 site model**

## 4.5 1:64 Detail Model Test Procedure

Figure 4.5. 1:64 Detail Model of WTC Atrium

A 1:64 scale model of the typical atrium configuration at WTC was constructed of plexi-glass, chipboard and wood. 1:64 was selected as the scale due to the level of detail that could be included. The model included seven segments of the roof assembly, the operable louvers at the exhaust ports on the roof spine and side inlets above the entries. Omni-directional airflow transducers, model TSI #8475, were placed at the atrium inlet, roof outlet and near the geometric center of the atrium. Because only three transducers were available separate tests were performed for each of the three atriums. For each series of atrium tests wind direction from eight directions (N, NE, E, SE….) was simulated at each of three different wind speeds (4,and 8 mph). For statistical reliability each test was repeated three times. Each test was run for five minutes with readings being taken at five-second intervals.

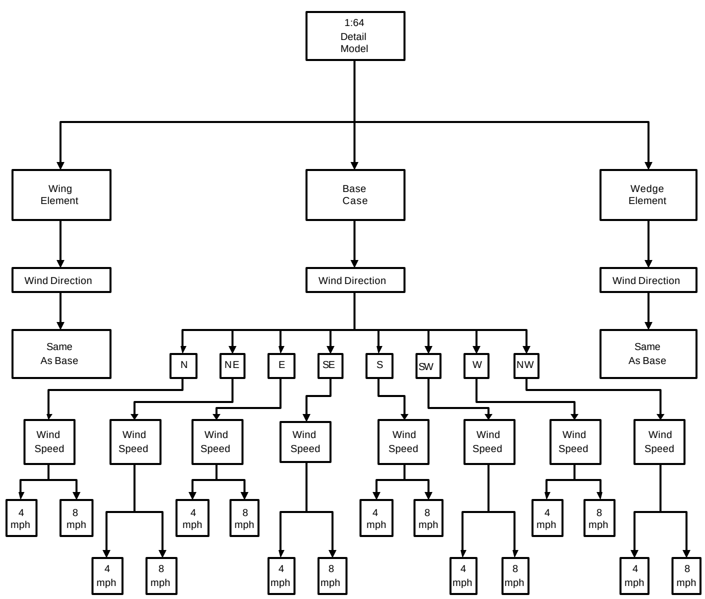


Figure 4.6. Test matrix for 1:64 detail model

Two roof top elements constructed of chipboard and cellophane were developed for use with the 1:64 detail model. The first element was known as the “wing” and had a profile similar to a football. This element was designed to use the principles of the Bernoulli effect. The second element was known as the “wedge” and was an extruded, inverted triangle. This element was designed to use the principles of the Venturi effect. Both elements were designed to study the positive or negative effects on the airflow rate at the roofline as well as the secondary effects at the interior and inlet locations of the model.

## 4.6 Test Facilities

All tests were performed in the Wind Tunnel Facility located at the Environmental Sciences Laboratory (ESL) at the Prices Fork Research Station. The wind tunnel is a relatively simple structure within a larger room that serves as the return and supply air plenums for the tunnel. Air is brought into the wind chamber via a large wind scoop with an opening of 32 square feet and then through a series of air straightening tubes.[3] These tubes position the air to come in at an even flow rate as it enters the test chamber. The test chamber is a room with an 8’x12’ table placed level with the bottom edge of the straighteners and the bottom of the fan blades. The fan chamber houses the main drive mechanisms for the wind tunnel and is the location where the air speeds are generated. The fans are twin 44” diameter 5-blade, belt-driven fan motors. Set in a 4’x8’ opening, which is aligned with the air intake, these two fans work together to pull air through the test chamber at a given speed. This is done to eliminate any long wave turbulence that the fan blades create as they push the air. A variable speed controller, the Toshiba ESP-130 transistor/inverter, controls the two fan motors. The controller has a maximum power supply of 230 volts and a maximum power generation of 80 Hertz. The fan frequency is correlated to air speed in order to convert into miles per hour. At full power the ESP-130 will generate a frequency of 80Hz at the fan motors, which corresponds to speed tests from 0 to 12 mph, and can be used to test wind orientation for all 360 degrees.


**Figure 4.7. Wind Tunnel Inverter**

### 4.6.1 Smoke Wand

The wind tunnel is also equipped with a simple smoke generator. This generator uses a small air pump, heater element and mineral oil to produce a

[3] For images of the Virginia Tech Wind Tunnel see Appendix D

small stream of smoke. This smoke is introduced into the flow stream via a smoke wand. The smoke wand is a small piece of pipe that allows wind in the tunnel to draw the smoke out. The smoke wand however has a very limited capacity and through trial and error it has been determined that the smoke wand works most efficiently at 2MPH

### 4.6.2 Test Apparatus Specification

During the test phase of this study **TSI Model #8475** air velocity transducers were used to measure the change in air flow rate due to wind position and wind speed at various locations on the models. The transducers also known as hot-wire anemometers send a small electric current through an exposed wire. This wire or node is placed into an airflow and measures the amount of resistance due to cooling that the current encounters. This resistance is then registered as an airflow rate in the on board computer chip. The TSI 8475 is designed to read the data in a number of ways and at a variety of voltages. For the purposes of these tests the hot-wire output was set at 1-5 volts with an effective recording range of 0-500 feet per minute. Thus a change of 1 volt in the hot wire was equivalent to a velocity change of 100 fpm. The transducers during these tests were also set to take readings every 5 seconds. The transducers recorded the data using analog means and through the use of a microchip converted the voltage data into a readable air speed using the following equation **4.1.**

$$V = (E_{out} - E_o)/(E_{FS} - E_o) \times V_{FS} \quad \text{EQ 4.1}$$

Where:

- $V$ = Measured Velocity (fpm)
- $V_{FS}$ = Full Scale Velocity setting (fpm)
- $E_{out}$ = Measured output voltage or current signal
- $E_o$ = Zero flow output voltage or current
- $E_{FS}$ = Full scale voltage or current output

The TSI #8475's also have a factory set accuracy range of +/- 1.0% of the full scale range. In other words with the effective range of these TSI's being 0-500 fpm any recorded value that is less than or equal to 5 fpm in relation to a constant air flow rate can be considered to be due to the apparatus and not the wind speed or direction acting on the transducer. During the course of this study this 5 feet per minute range of error was only generated in one or two isolated instances.

Once the data was recorded by the TSI #8475 the data was transferred into the Campbell Scientific (CSI) 21x data logger, where the data was converted into a digital format. The data transfer was achieved through a high voltage and low voltage lead wires that ran from the TSI into the analog ports on the data logger. The 21x data logger then converted the analog data to digital with percent error of 0.1%. The data logger having been manually programmed to convert the incoming data into the desired value structure placed the data into an 8-bit binary format, which was stored in a memory chip in the data logger. This binary data was then transferred into a SM192 storage module (made by Campbell Scientific) for transport to a computer station. Once the SM192 was connected to a computer through a serial port the binary data was converted into a delimited format for spreadsheets using Campbell's CS208 software package.[4]

### 4.6.3 Data logger Setup

The data logger used for this study was a Campbell Scientific Inc. 21x Micro-logger, which can store 18,000 points of data in its memory chip. The 21x was supplied with 12 volts and as long as it was kept in a powered condition it would maintain any program sequence that was entered into it. The storage capabilities of the data logger were such that one complete 24-test series could be stored in the onboard memory. After every test series the data were downloaded to a battery powered storage module. This module, the SM-192 data storage module by Campbell Scientific Inc., was connected to the data logger with a patch cord to allow for easy data transfer. Each storage module could then hold up to 59,000 data points, which in the scope of this study was a complete 3 series data set for any given location. Once the information was complied on the SM-192 the 21x logger's memory could be erased and the next test series could be started. At the end of each test day the SM-192 module was then connected to a computer using the CS-208 software by Campbell Scientific Inc., and the data were then downloaded to the local hard drive. After this process the storage module's memory was then erased creating storage space for subsequent tests.

**Figure 4.8. Datalogger and transducers**

## 4.7 Qualitative Tests

The first series of tests to be run were the visualization tests. These were simple tests using the smoke wand and a zinc oxide powder apparatus to understand the general flow of air through, in, over and around the models. On the 1:250 model particular attention would be paid to the effect of the towers in regard to wind orientation on the flow of air over the atrium roofs, as well as the effects of the roof overhangs at the inlets and the overall roof profile's influence on the exhaust ports. All atriums were tested individually at all critical points and finally the entire complex was tested for general wind patterns. All of the tests were

[4] All technical data and specifications concerning the test apparatus comes directly from the TSI and CSI user manuals for each specific device.

charted at the eight predetermined orientations and wind speeds. The 1:64 model would likewise undergo a similar set of tests with the focus being the roof system. Particular attention was paid to the effect of the existing roof louvers at the exhaust ports, as well as the additional effects of the wing and wedge elements that were added.

When setting up the parameters for the visualization tests the initial inclination was to use traditional camera and video technology to capture images. While these tools would have been most likely successful the ability to convert these analog images into a digital format was definitely a concern. Likewise the relative slow turn around time for development along with the costs involved with the film was also seen as negative aspects. Therefore digital technology was used. Images were recorded on a **Kodak Dc 215 Zoom** digital camera with a 32-megabyte memory card. Images were taken at an 1152x864 pixel resolution and were processed using Adobe Photoshop 5.5. A total of 108 images were used to document the tests for both the 1:250 scale model and the 1:64 detail model.

## Chapter 5: Data Analysis

Wind tunnel tests were performed for each atrium or roof design for each of the four primary and four secondary wind direction and for each level of wind speed as presented in **Figure 4.5** and **4.6**. Data were collected and stored in a Campbell Scientific 21x micrologger. The data were analyzed using tests for statistical inference and analysis for variance. Data were analyzed for the 1:250 and 1:64 scale models separately.

### 5.1 Statistical Tests

The data were analyzed using tests for statistical inference and analysis of variance using regression techniques. When performing these tests three resultant values are important, these values can be interpreted from **equation 5.1**

$$\underset{}{Y} = b_o + \underset{(t_1)}{b_1 x_1} + \underset{(t_2)}{b_2 x_2} + \ldots\ldots \underset{(t_n)}{b_n x_n} \qquad \text{EQ 5.1}$$

Where:
- **$Y$** = the dependant variable
- **$x_1 - x_n$**= the independent variables
- **$b_o$**= the intercept
- **$b_1 - b_n$**= partial slope coefficients
- **$t_1 - t_n$** = t-values for test for significance

In **equation 5.1** the value of the partial slope coefficients (**$b_1 - b_n$**) represent the linear relationship between the dependant variable (**Y**) and the respective independent variable. The t-values represent the test for significance for the respective independent variable. Generally, t-values greater than +2.0 or less that –2.0 suggest statistical significance for the independent variable. Values greater than +2.0 or less than –2.0 also indicate that the $X_n$ term is significant for predicting **Y** thus **$X_n$** belongs in the model.

Models such as **equation 5.1** can be used to draw inferences and quantify estimated effects of variables. For example it was desirable to quantify the airflow rate (AFR) inside each atrium as a function of changes in wind speed. This is modeled in **equation 5.2** for three wind speeds.

$$AFR = b_o + \underset{(t_1)}{b_1(\text{wind speed 1})} + \underset{(t_2)}{b_2(\text{wind speed 2})} \qquad \text{EQ 5.2}$$

Notice that the model in **equation 5.2** includes only two wind speeds. This is because the inclusion of all levels of a categorical variable would result in improper matrix inversion during the analysis. Therefore in **equation 5.2** the partial slope coefficients (**$b_1$ & $b_2$**) indicate the average change in the AFR as conditions vary from speed 3, the one left out, and to wind speed 1, and wind speed 2 respectively. The t-values for each wind speed provide evidence that the change in wind speed that resulted in an AFR are statistically different than those recorded for speed 3 (the one left out). This approach was used to quantify the differences in airflow rate resulting from the variable conditions shown in **Figures 4.5** and **4.6**.

## 5.2 1:250 Model

The large 1:250 model as mentioned before was designed for the purpose of studying the overall flow patterns in each atrium due to variations in wind direction and wind speed. Data from these tests were broken down into sub categories based on wind speed and direction. The data were then compiled into large master files that incorporated all data for a given atrium. The data were then converted into another spreadsheet using the statistical software Stat View. For the 1:250 model the goal was to analyze the data in two separate ways. The first analysis used transducer location (inlet, interior and rooftop) as the dependant variable and seven of the eight wind directions as the independent variables. For the sake of continuity the west direction (position 1) was always left out and served as the base condition for all other wind directions. The estimates for the airflow rates were plotted for each wind orientation for each location of the airflow transducer (inlet, interior, roof). Similar charts were plotted for each atrium test. The result for the west, middle and east atriums are shown in **charts 5.1** through **5.9** respectively.

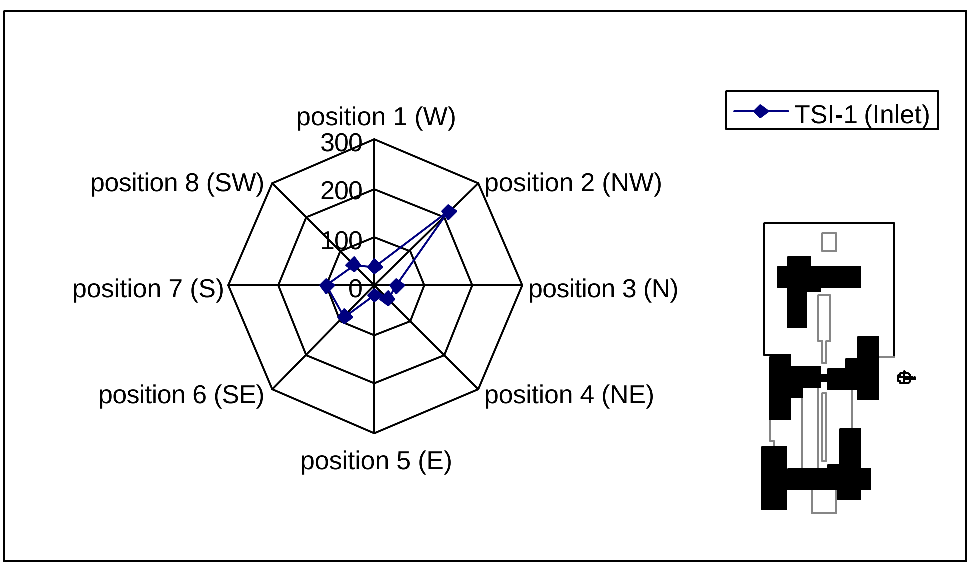


**Chart 5.1. Change in AFR at West atrium inlet due to change in wind direction (in fpm)**

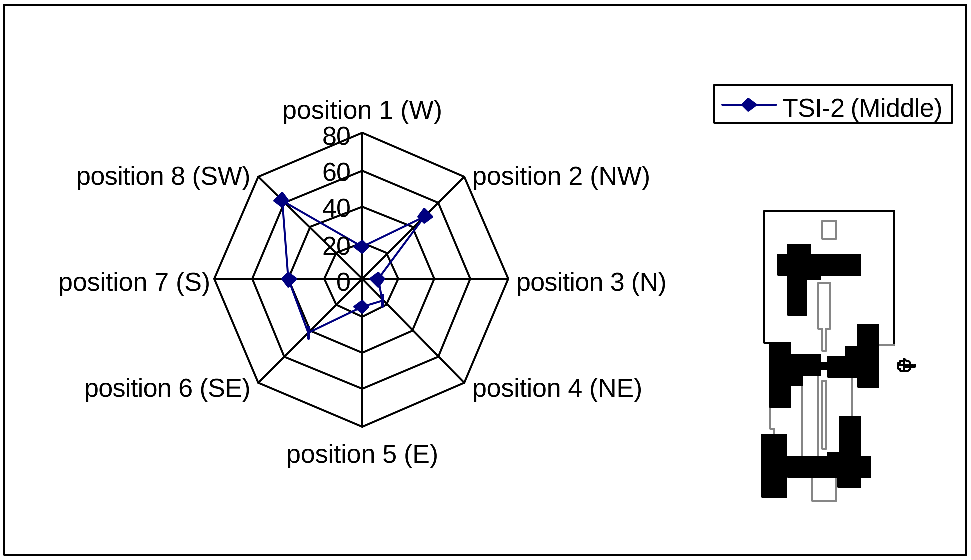


**Chart 5.2. Change in AFR at West atrium interior due to change in wind direction (in fpm)**

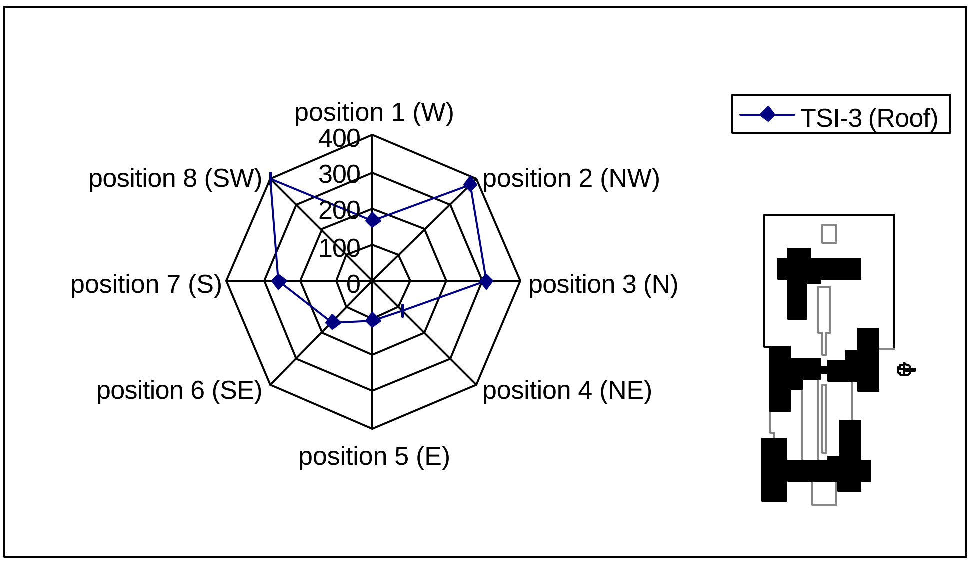


**Chart 5.3. Change in AFR at West atrium roof due to change in wind direction (in fpm)**

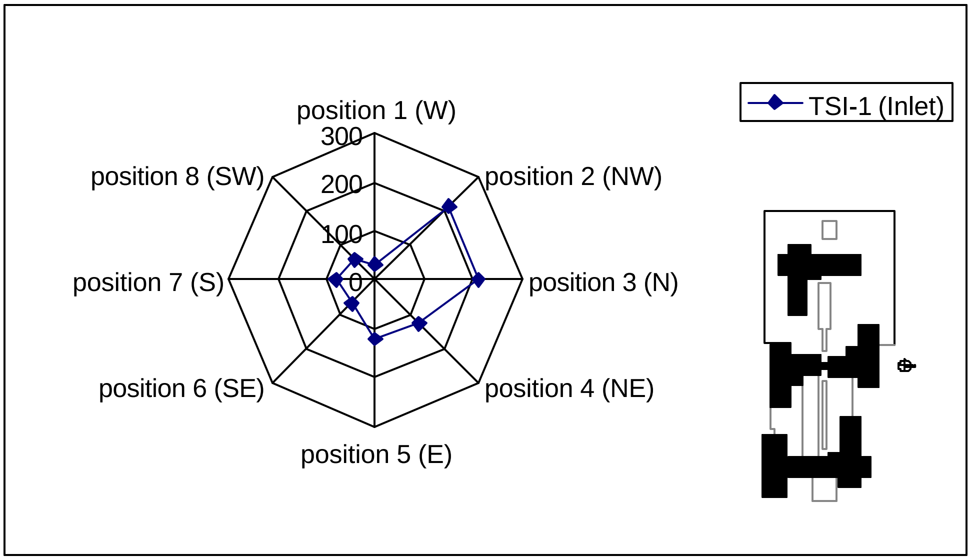


**Chart 5.4. Change in AFR at Middle atrium inlet due to change in wind direction (in fpm)**

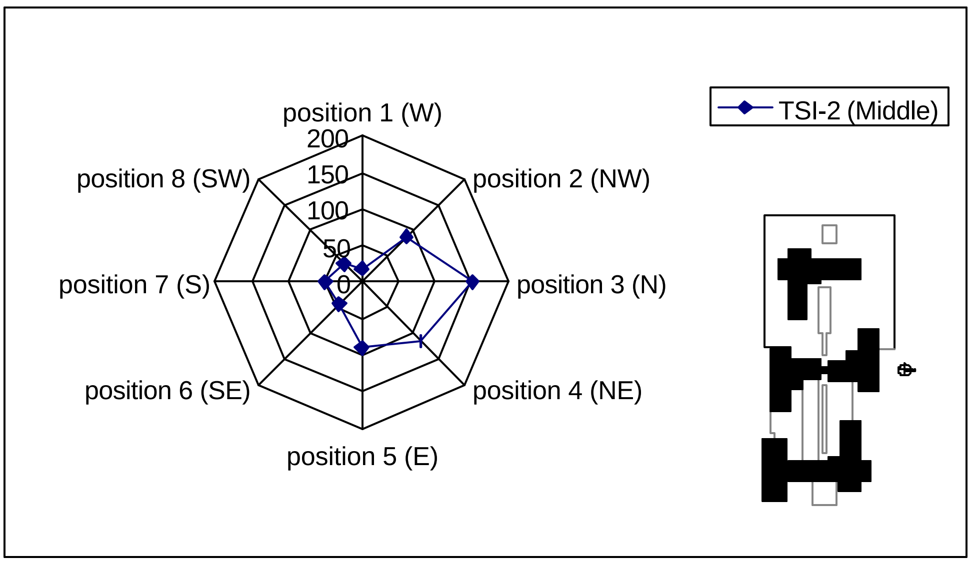


**Chart 5.5.Change in AFR at Middle atrium interior due to change in wind direction (in fpm)**

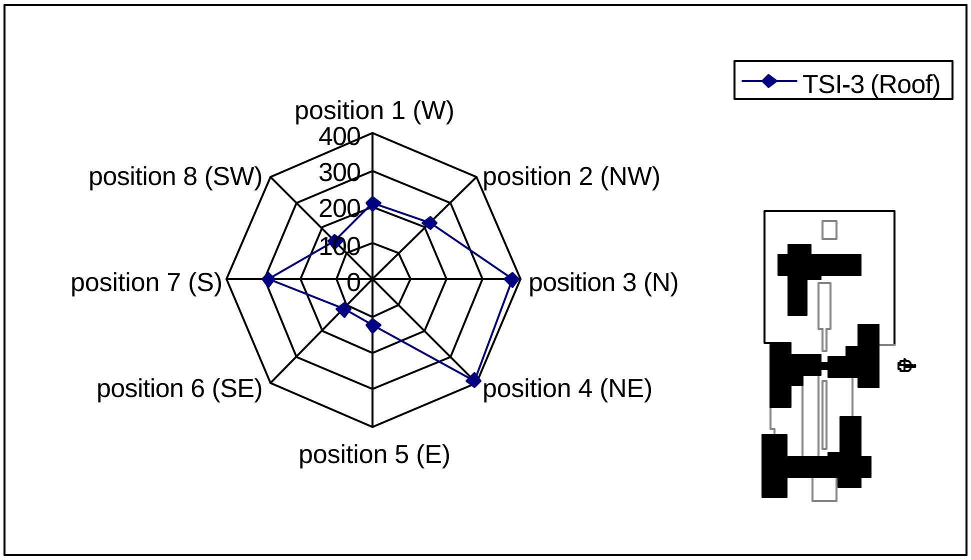


**Chart 5.6. Change in AFR at Middle atrium roof due to change in wind direction (in fpm)**

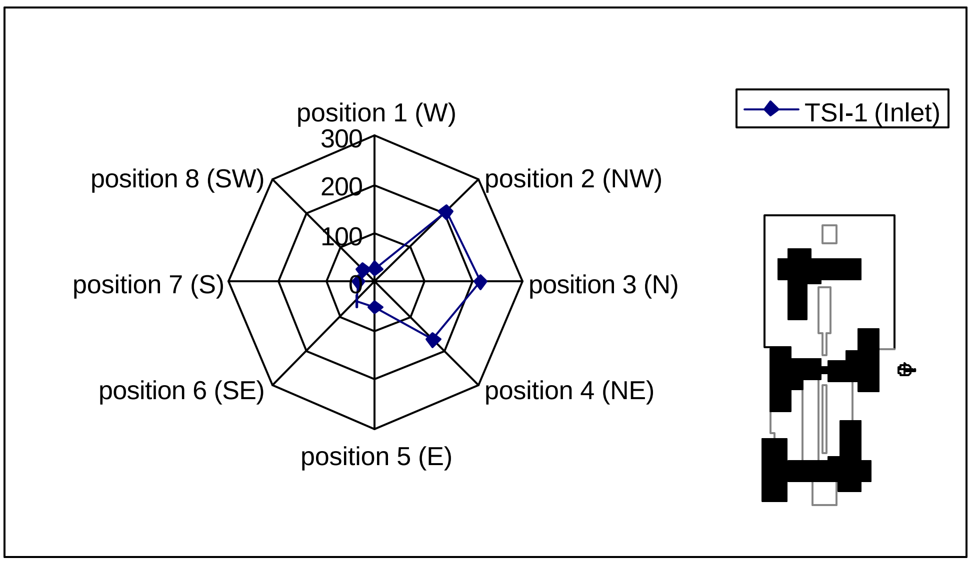


**Chart 5.7. Change in AFR at East atrium inlet due to change in wind direction (in fpm)**

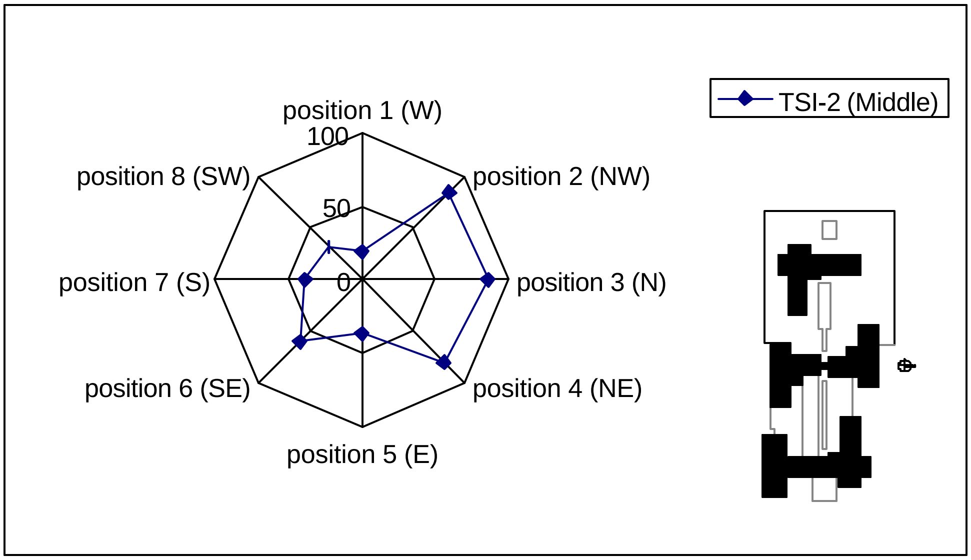


**Chart 5.8. Change in AFR at East atrium interior due to change in wind direction (in fpm)**

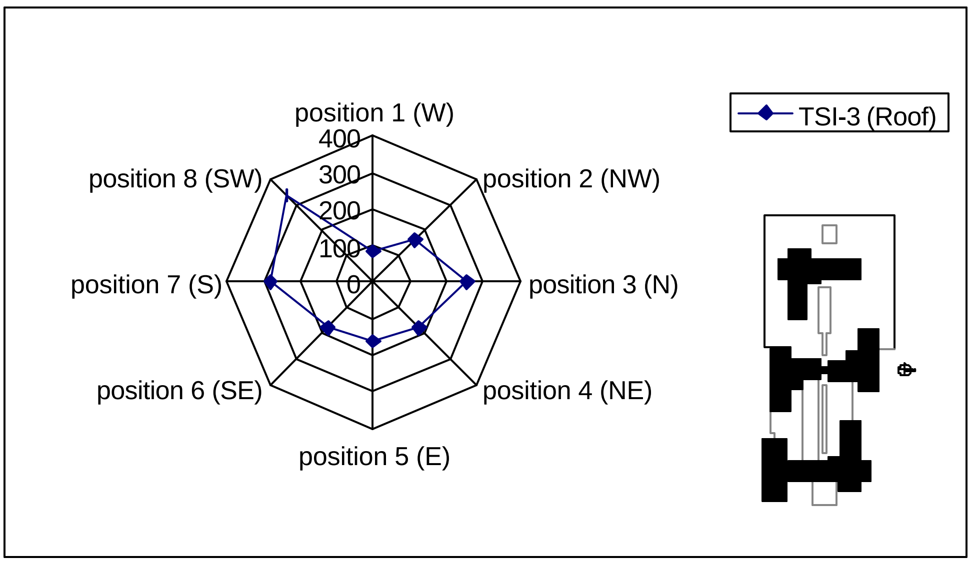


**Chart 5.9. Change in AFR at East atrium roof due to change in wind direction (in fpm)**

For numerical values for **Charts 5.1** through **Chart 5.9** see **Appendix B**
The tests for significance (t-values) are summarized in **Table 5.1**.

| | East Atrium | | | Middle Atrium | | | West Atrium | | |
|---|---|---|---|---|---|---|---|---|---|
| | TSI-1 | TSI-2 | TSI-3 | TSI-1 | TSI-2 | TSI-3 | TSI-1 | TSI-2 | TSI-3 |
| **West (1)** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| **N. West (2)** | 57.55 | 45.66 | 13.06 | 57.51 | 36.02 | 1.78 | 74.46 | 33.55 | 31.84 |
| **North (3)** | 61.13 | 46.79 | 29.11 | 56.75 | 69.54 | 29.03 | 2.46 | -9.92 | 21.66 |
| **N. East (4)** | 45.55 | 42.07 | 15.49 | 29.94 | 50.13 | 30.37 | -1.06 | -1.69 | -8.42 |
| **East (5)** | 7.86 | 12.46 | 12.91 | 28.27 | 37.38 | -13.99 | -8.80 | -3.66 | -9.61 |
| **S. East (6)** | 8.97 | 28.15 | 15.55 | 11.57 | 12.65 | -15.87 | 20.83 | 24.80 | -1.92 |
| **South (7)** | 2.59 | 13.58 | 33.50 | 15.54 | 16.30 | 13.18 | 25.25 | 23.07 | 13.79 |
| **S. West (8)** | 2.51 | 8.93 | 42.66 | 8.21 | 8.57 | -10.08 | 10.32 | 46.69 | 35.11 |

**Table 5.1. T-value for significance tests for all atriums due to change in wind direction**

### 5.2.1 Change In Airflow Due to Wind Speed

A second series of analyses were run on the 1:250 model to determine the change in the airflow rate at the inlet, interior and roof locations due to changes in wind speed and direction. In this sequence the transducer locations were again set as the dependant variable and the wind directions 2 through 8 were used as the independent variables. However in addition to directions 2 through 8 the category of wind speed was also added to the independent variable list. Much like in the first series of regression analyses the changes in the average airflow rate (AFR) at each transducer location were charted in relation to a constant value at wind direction 1. The wind speed data that was used with the wind directions as the independent variables had also been taken from the original spreadsheets that had broken the speed out into 4,8 and 12 mile per hour sub-sets. In effect the results indicate the predicted change in the airflow rate due to an increase of one mile per hour in wind speed. The results of these regressions are shown in **chart 5.10** and the tests for significance values are shown in **Table 5.2**.

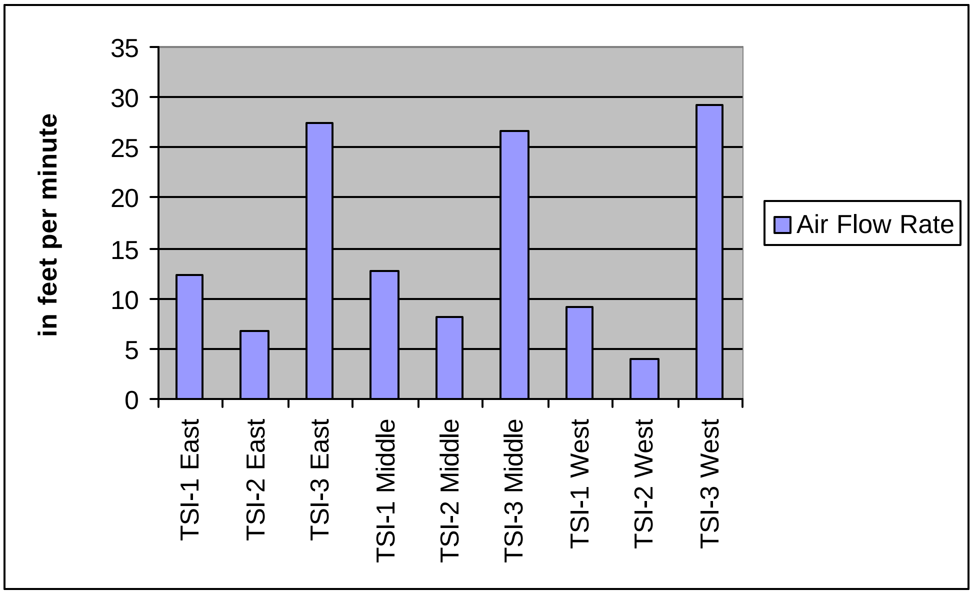


**Chart 5.10. Comparison of change in wind speed on AFR at all transducer locations (in fpm)**

| Transducer Location | T-value |
|---|---|
| TSI-1 East | 86.36 |
| TSI-2 East | 154.78 |
| TSI-3 East | 161.52 |
| TSI-1 Middle | 86.77 |
| TSI-2 Middle | 102.36 |
| TSI-3 Middle | 127.43 |
| TSI-1 West | 78.28 |
| TSI-2 West | 107.83 |
| TSI-3 West | 126.85 |

**Table 5.2. T-value for significance tests for all atriums due to change in wind speed (in fpm)**

## 5.3 Airflow Due to Wind Speed and Direction

A third analysis procedure grew out of the findings from the first and second procedures. The third regression series sought to determine the change in the airflow rate (in fpm) at each transducer location in regards to a change in wind speed and direction. This in effect required that each transducer location be run through eight regressions, one for each wind direction. Also in this regression series wind direction 1 (west) was included. The estimated average change in airflow at the inlet, interior and roof were determined for each of the three atriums and are shown in **charts 5.11** though **5.19**.

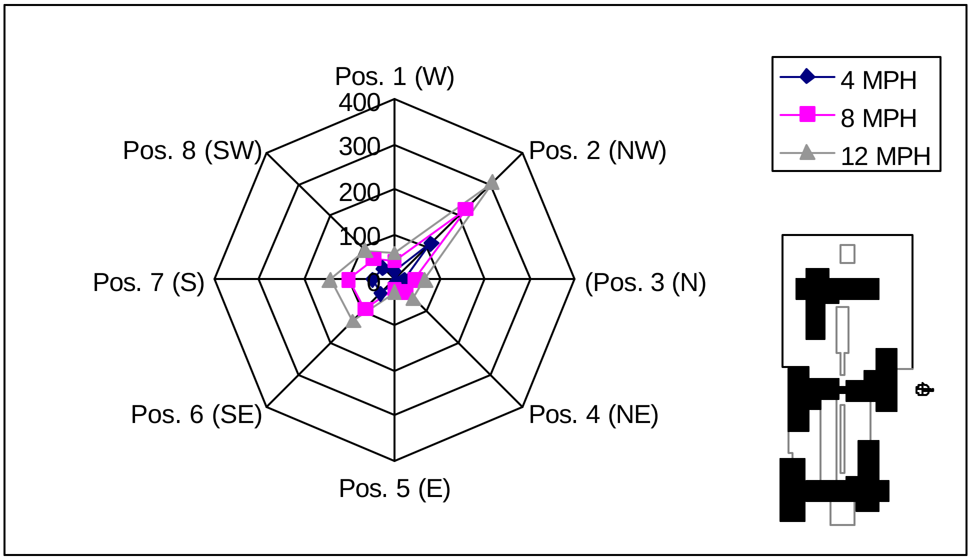


**Chart 5.11. Mean AFR at West atrium inlet for all wind directions and three wind speeds (In fpm)**

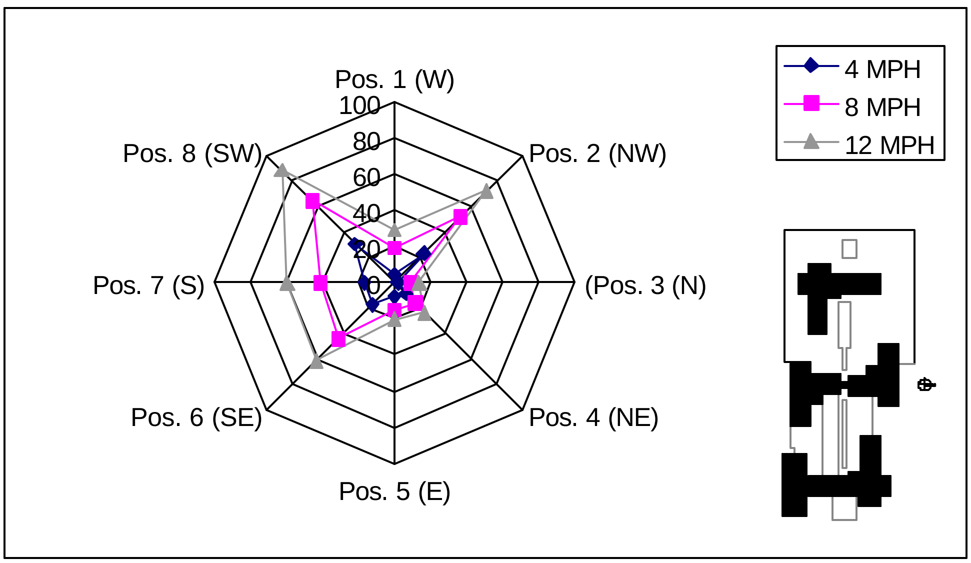


**Chart 5.12. Mean AFR at West atrium interior for all wind directions and three wind speeds (In fpm)**

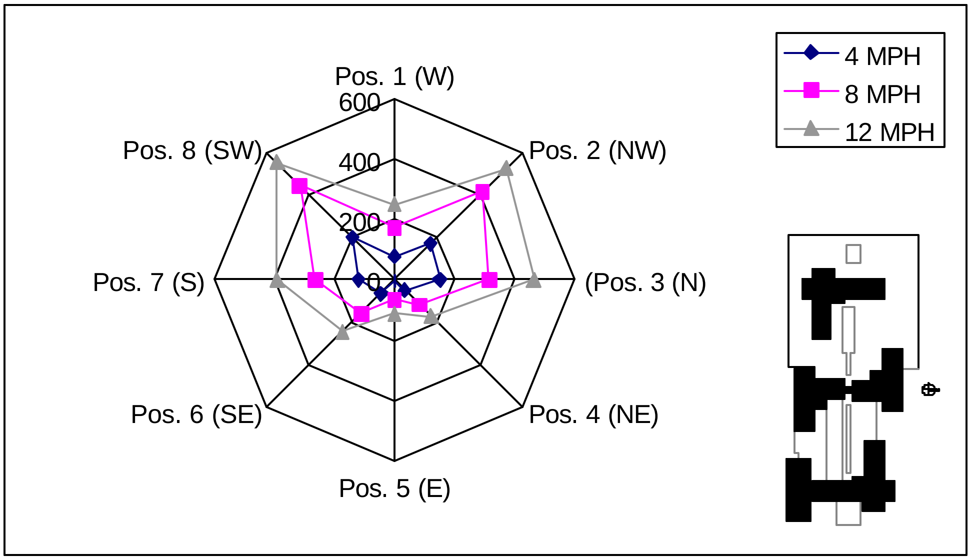


**Chart 5.13. Mean AFR at West atrium roof for all wind directions and three wind speeds (in fpm)**

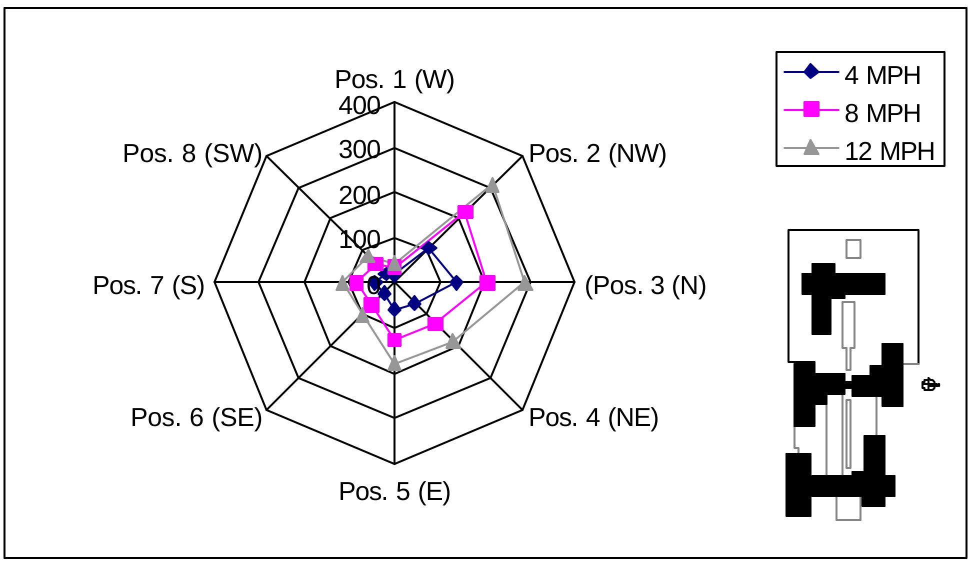


**Chart 5.14. Mean AFR at Middle atrium inlet for all wind directions and three wind speeds (in fpm)**

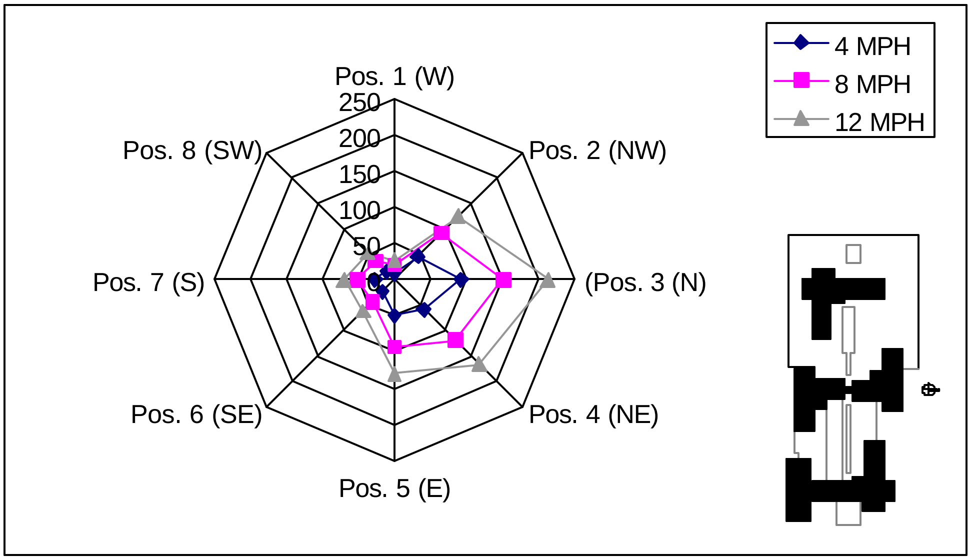


**Chart 5.15. Mean AFR at Middle atrium interior for all wind directions and three wind speeds (In fpm)**

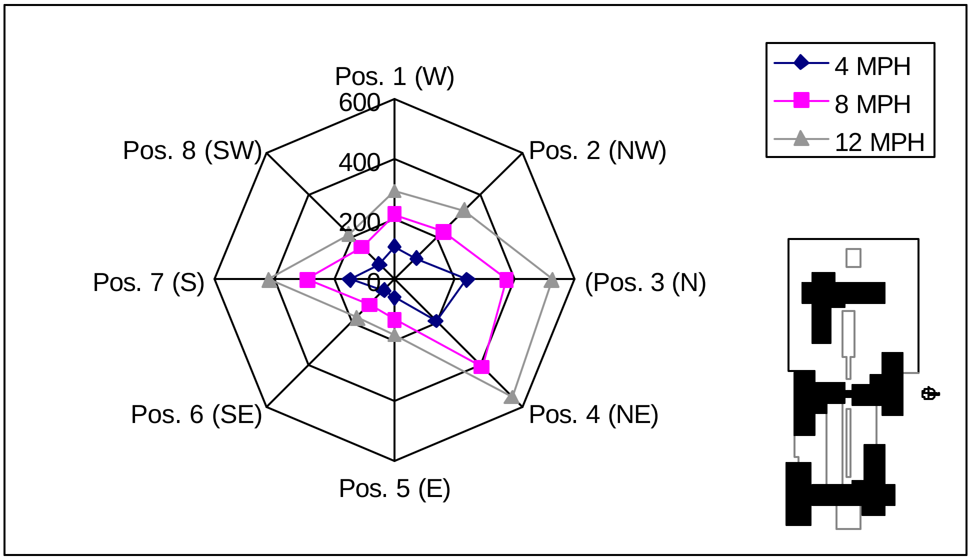


**Chart 5.16. Mean AFR at Middle atrium roof for all wind directions and three wind speeds (in fpm)**

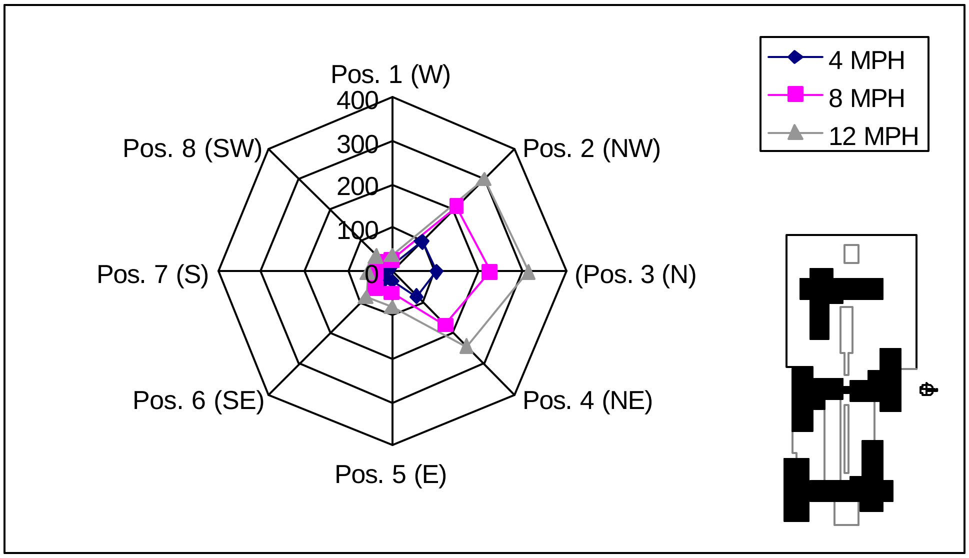


**Chart 5.17. Mean AFR at East atrium inlet for all wind directions and three wind speeds (in fpm)**

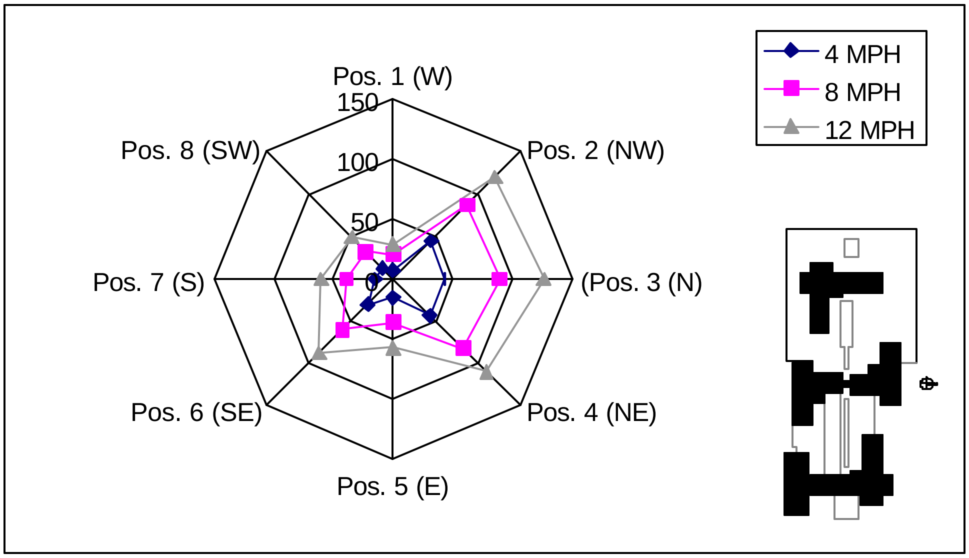


**Chart 5.18. Mean AFR at East atrium interior for all wind directions and three wind speeds (in fpm)**

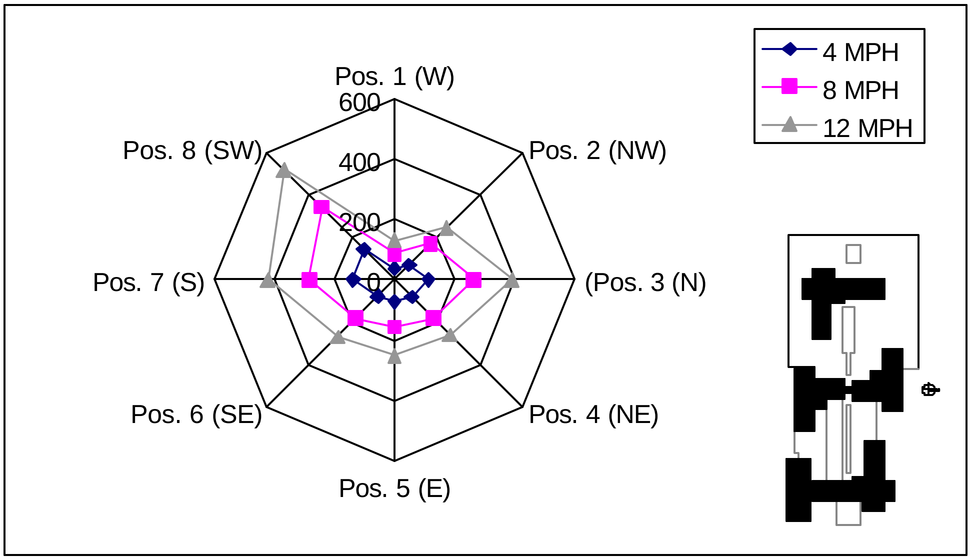


**Chart 5.19. Mean AFR at East atrium roof for all wind directions and three wind speeds (in fpm)**

For numerical values for **Charts 5.11** through **Chart 5.19** see **Appendix B**
The tests for significance (t-values) are summarized in **Table 5.3** through **5.5**.

| | | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|---|
| | **TSI-1** | 49.89 | 26.61 | 86.96 | 37.79 | 61.80 | 110.23 | 109.13 | 131.48 |
| **8MPH** | **TSI-2** | 38.89 | 36.86 | 43.65 | 27.54 | 48.22 | 133.38 | 88.78 | 66.92 |
| | **TSI-3** | 46.22 | 37.90 | 74.46 | 50.50 | 78.85 | 141.51 | 88.30 | 75.93 |
| **12MPH** | **TSI-1** | 87.08 | 46.83 | 162.72 | 74.83 | 107.88 | 200.43 | 194.98 | 240.96 |
| | **TSI-2** | 66.42 | 62.94 | 69.38 | 53.36 | 81.72 | 221.49 | 154.83 | 114.12 |
| | **TSI-3** | 83.68 | 54.72 | 143.14 | 92.30 | 138.04 | 267.07 | 165.78 | 108.73 |

**Table 5.3. T-value for significance tests for West atrium for all wind directions and wind speeds.**

| | | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|---|
| | **TSI-1** | 78.11 | 60.66 | 10.98 | 41.32 | 146.80 | 92.51 | 106.17 | 112.61 |
| **8MPH** | **TSI-2** | 36.29 | 59.12 | 23.49 | 73.12 | 65.31 | 33.85 | 59.53 | 69.67 |
| | **TSI-3** | 117.62 | 23.69 | 19.21 | 160.60 | 100.33 | 83.75 | 94.10 | 44.74 |
| **12MPH** | **TSI-1** | 115.61 | 107.38 | 24.56 | 76.20 | 257.16 | 163.66 | 784.21 | 199.35 |
| | **TSI-2** | 56.64 | 102.46 | 48.20 | 127.86 | 119.87 | 83.75 | 104.27 | 122.62 |
| | **TSI-3** | 203.45 | 42.55 | 41.46 | 267.68 | 168.13 | 155.74 | 177.83 | 77.70 |

**Table 5.4. T-value for significance tests for Middle atrium for all wind directions and wind speeds.**

| | | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|---|
| | **TSI-1** | 32.98 | 153.54 | 183.48 | 122.40 | 27.38 | 31.75 | 118.31 | 41.40 |
| **8MPH** | **TSI-2** | 31.37 | 88.99 | 88.05 | 154.29 | 49.17 | 33.93 | 124.51 | 74.36 |
| | **TSI-3** | 51.18 | 249.23 | 193.17 | 220.58 | 24.80 | 193.93 | 92.18 | 165.94 |
| **12MPH** | **TSI-1** | 58.90 | 273.55 | 315.72 | 211.88 | 59.94 | 69.06 | 212.42 | 82.31 |
| | **TSI-2** | 50.97 | 159.10 | 158.06 | 265.18 | 100.37 | 65.95 | 231.35 | 136.27 |
| | **TSI-3** | 96.32 | 440.46 | 357.85 | 393.35 | 52.87 | 356.02 | 178.44 | 313.71 |

**Table 5.5. T-values for significance tests for East atrium for all wind directions and wind speeds.**

## 5.4 Detail Model

A second series of analyses were performed for the 1:64 scale model. These analyses allowed for comparison of ventilation conditions for the base case and for two proposed roof designs. Analyses were performed similar to those of the 1:250scale model. Analyses of variance and regression analysis were used to quantitatively estimate changes in the airflow rate as a result of variations in wind direction and speed. As before the partial slope coefficient provided and unbiased estimate of the effect while the t-values are tests for significance. The results for the addition of the wing and wedge elements at 4mph are show in **charts 5.20** through **5.22**. Results for the wing and wedge element at 8 mph are summarized in **charts 5.23** through **5.25**.

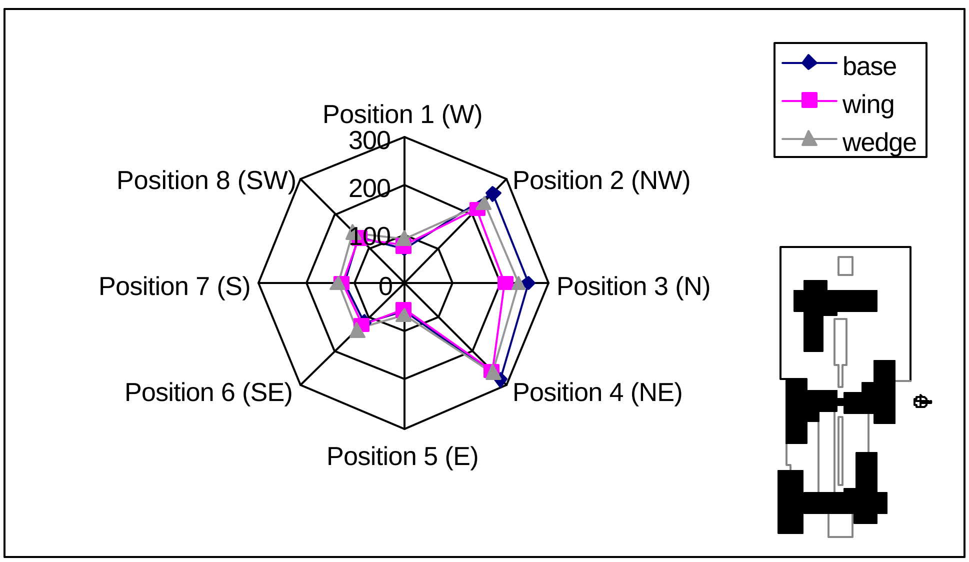


**Chart 5.20. Change in AFR at inlet for 4 mph for all wind directions and roof variations (in fpm)**

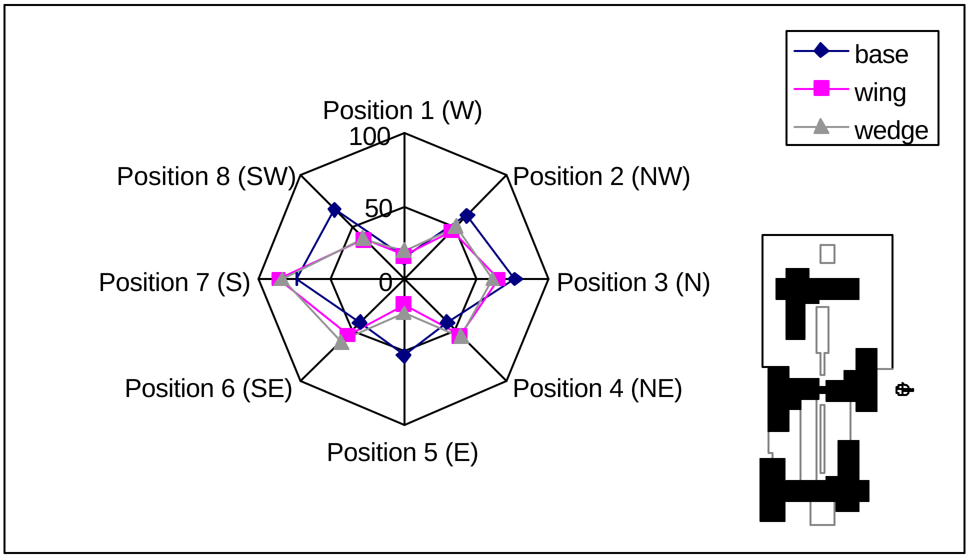


**Chart 5.21. Change in AFR at interior for 4 mph for all wind directions and roof variations (in fpm)**

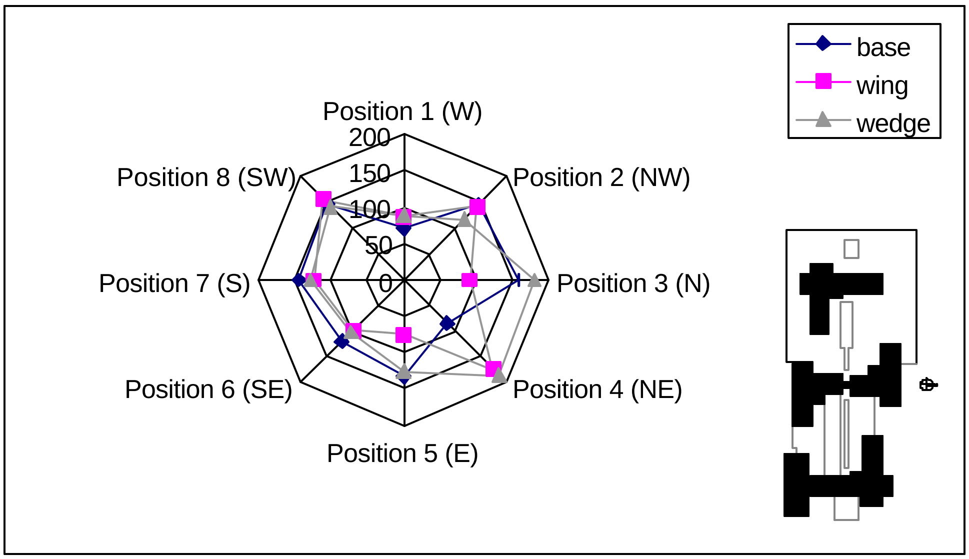


**Chart 5.22. Change in AFR at roof for 4 mph for all wind directions and roof variations (in fpm)**

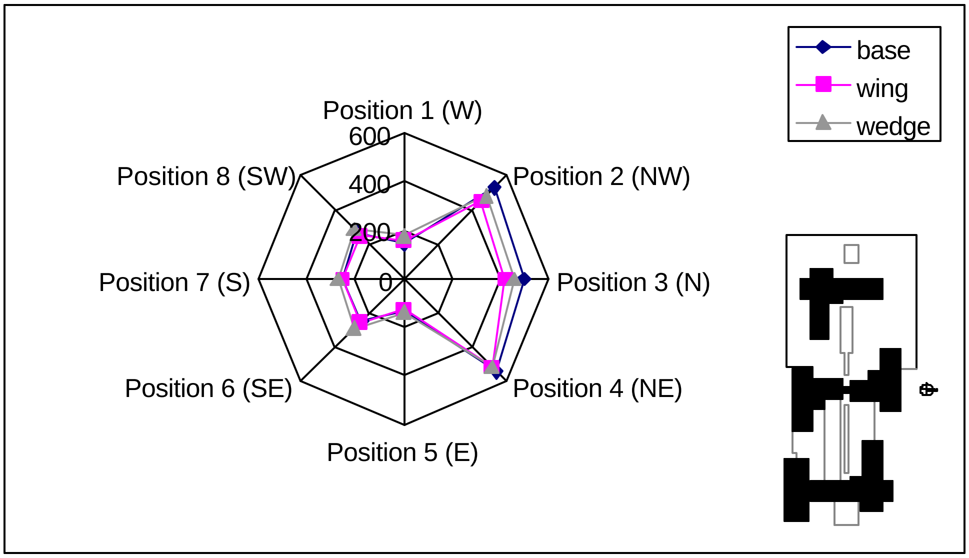


**Chart 5.23. Change in AFR at inlet for 8 mph for all wind directions and roof variations (in fpm)**

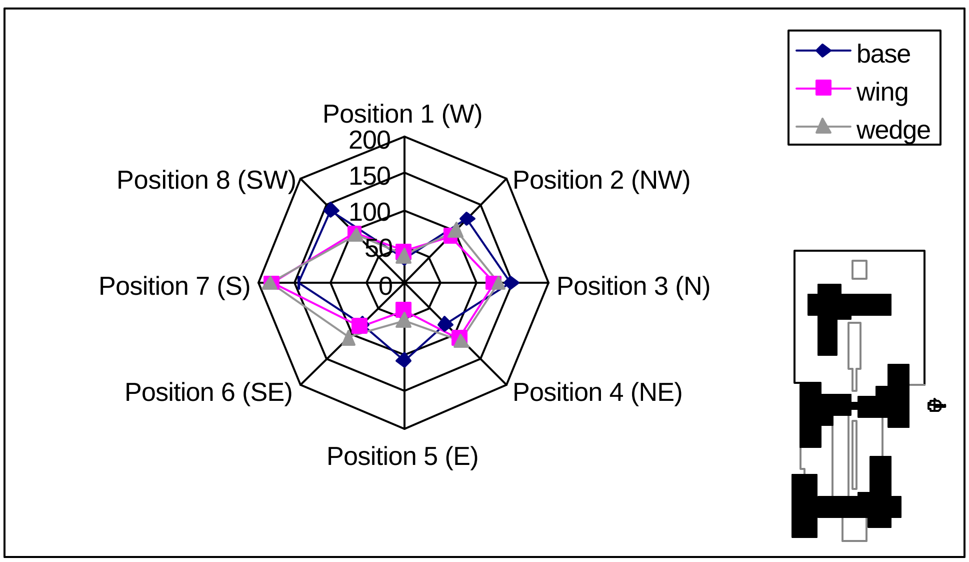


**Chart 5.24. Change in AFR at interior for 8 mph for all wind directions and roof variations (in fpm)**

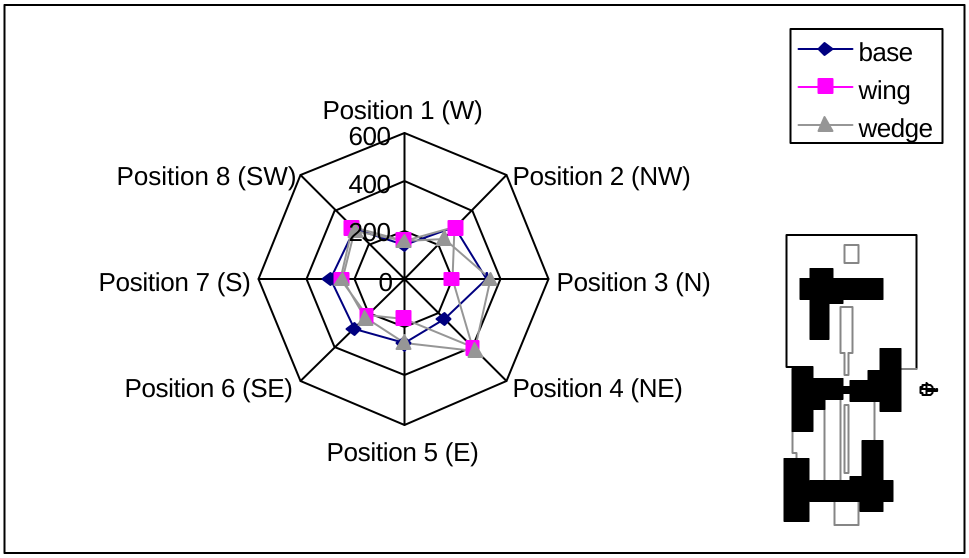


**Chart 5.25. Change in AFR at roof for 8 mph for all wind directions and roof variations (in fpm)**

For numerical values for **Charts 5.20** through **Chart 5.25** see **Appendix B**
The tests for significance (t-values) are summarized in **Table 5.6** through **5.7**.

| | | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|---|
| | **TSI-1** | 9.95 | -42.49 | -33.04 | -16.87 | -5.19 | 8.39 | 6323.00 | -2.57 |
| **Wing** | **TSI-2** | 4.69 | -34.17 | -14.76 | 31.28 | -91.27 | 20.20 | 8.23 | -68.53 |
| | **TSI-3** | 16.05 | -4.67 | -50.84 | 801.68 | -82.06 | -18.37 | -14.64 | 8.99 |
| | **TSI-1** | 31.66 | -24.92 | -13.50 | -14.23 | 11.10 | 28.89 | 16.13 | 19.85 |
| **Wedge** | **TSI-2** | 16.88 | -24.06 | -19.55 | 32.08 | -75.97 | 31.18 | 9.94 | -64.99 |
| | **TSI-3** | 18.32 | -31.96 | 17.12 | 92.01 | -9.52 | -16.31 | -18.53 | -6.79 |

**Table 5.6. T-values for significance tests for 1:64 model at 4mph for all wind directions and roof variations.**

| | | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|---|
| | **TSI-1** | 14.12 | -40.29 | -26.30 | -14.49 | -2.76 | 5.54 | 0.49 | -16.77 |
| **Wing** | **TSI-2** | 10.33 | -45.86 | -14.61 | 40.72 | -94.55 | 3.47 | 14.16 | -61.26 |
| | **TSI-3** | 5.06 | -1.39 | -55.57 | 89.06 | -97.49 | -33.06 | -19.11 | 5.94 |
| | **TSI-1** | 30.67 | -24.49 | -14.53 | -14.36 | 7.74 | 30.21 | 11.31 | 15.41 |
| **Wedge** | **TSI-2** | 4.74 | -30.54 | -19.56 | 49.06 | -75.45 | 23.39 | 15.10 | -64.23 |
| | **TSI-3** | 4.35 | -36.34 | 4.59 | 96.89 | -5.76 | -28.12 | -21.54 | -4.84 |

**Table 5.7. T-values for significance tests for 1:64 model at 8mph for all wind directions and roof variations.**

## 5.5 Conclusions of Data Analysis

In this chapter the slope coefficient values and t-values were placed into a series of charts and tables. These graphic methods were used as a medium for representing the collected data samples. Charts were created to show the significance of changes in wind speed and direction on the 1:250 model. Charts were also generated to represent the significance of changes in wind speed, direction as well as changes in the roof configuration for the 1:64 model. The next chapter will serve as a medium through which the results of the aforementioned data can be discussed. The next chapter will also serve as the concluding remarks for this study.

## Chapter 6: Results and Conclusions

Throughout the course of this study the primary objective has always been to gain a better understanding of the ventilation strategies as designed by KPFI at the World Trade Center in Amsterdam. In conjunction with this understanding the development of possible improvements to the design was also seen as an objective. Likewise this thesis study also had secondary objectives. The first was to gain a better understanding of the feasibility of natural ventilation for large structures. The second was to clearly define the numerous ventilation strategies available and how they can be applied to all structures. From this investigation the following results and conclusions can be made

### 6.1 Effect of Towers

One of the most critical objectives of this study was to determine whether or not the towers created dead spots on the atrium roof systems. A corollary to this objective was also the study of the towers' effects on the wind patterns over the atrium roof systems. The following are the resulting conclusions from the data analysis.

1. For the west atrium the high-rise towers limit ventilation when the winds are out of the northern, southern and eastern quadrants. Maximum ventilation efficiency occurs when the winds are out of the northwest and southwest. The change in airflow at the interior of the west atrium ranged from 8.77 fpm at the north position to 61.46 fpm at the southwest position.

2. For the middle atrium the high-rise towers limit ventilation when the winds are out of the east, west, southwest and southeast directions. Maximum ventilation efficiency occurs when the winds are out of the north, northeast and northwest directions. The change in airflow at the interior of the middle atrium ranged from 18.00 fpm at the west position to 151.35 fpm at the north position.

3. For the east atrium the high-rise towers limit ventilation when the winds are out of the east and west directions. Maximum ventilation efficiency occurs when the winds are out of the northwest, northeast and southwest directions. The change in airflow at the interior of the east atrium ranged from 19.00 fpm at the west position to 85.97 fpm at the north position.

4. It should be noted that these values reflect the fact that airflow transducers were placed at the inlet on only one side of the atrium (north wall). It can be assumed that if transducers had been set on the opposite wall as well similar values would have been recorded on the south wall as well.

## 6.2 Effects on Air Flow Due To Change In Air Speed

Studying the changes in air speed on the complex was developed in order to understand the relation of wind speed on the negative pressure roof system. In this case the related objective was the validation of the WTC's negative pressure roof system.

1. For the west atrium the change in wind speed from 4 mph to 8 and 12 mph is most effective when winds are from the northwest, and southwest directions. The effects of the change in wind speed are least effective when winds are out of the north, east and west directions. At 8 mph the change in airflow at the interior of the west atrium ranges from 9.44 fpm at the north position to 64.44 fpm at the southwest position. At 12 mph the change in airflow ranges from 13.83 fpm at the north position to 88.35 fpm at the southwest position.

2. For the middle atrium the change in wind speed from 4 mph to 8 and 12 mph is most effective when the winds are from the northern directions (N, NE, NW). The effects of the change in wind speed are least effective when winds are out of the east, west and southwest directions. At 8 mph the change in airflow at the interior of the middle atrium ranges from 20.17 fpm at the west position to 150.86 fpm at the north position. At 12 mph the change in airflow at the interior ranges from 26.77 fpm at the west position to 212.26 fpm at the north position.

3. For the east atrium the change in wind speed from 4 mph to 8 and 12 mph is most effective when the winds are from the north, northeast and southwest. The effects of the change in wind speed are least effective when the winds are out of the east and west directions. At 8 mph the change in airflow at the interior of the east atrium ranges from 20.43 fpm at the west position to 88.93 fpm at the north position. At 12 mph the change in airflow at the interior ranges from 28.63 fpm at the west position to 125.69 fpm at the north direction.

## 6.3 Effects of Air Speed on Air Changes Per Hour

One of the most critical results of the recorded air flow rates through the atrium spaces were the air changes per hour (ACH). ACH represents the number of times per hour that the complete volume of air within a space is replaced by fresh air. For the purposes of this study the minimum and maximum air changes per hours were calculated for each atrium using the following equation **6.1**

$$\frac{(AFR \times A_{inlet} \times 60)}{V} = ACH \qquad \text{EQ 6.1}$$

Where: **AFR** = Air Flow Rate (in feet per minute)
**$A_{inlet}$** = Area of Inlet (in square feet)
**60** = Time Constant (in minutes per hour)
**V** = Volume (in cubic feet)
**ACH** = Air Changes Per Hour

1. For the west atrium the minimum air change per hour was calculated to be 2.93 ACH when weather and wind conditions were poor. However a maximum air change per hour was calculated at 34 ACH when wind and weather conditions were optimal.

2. For the middle atrium the minimum air change per hour was calculated to be 4.5 ACH when weather and wind conditions were poor. However a maximum air change per hour was calculated at 29.9 ACH when wind and weather conditions were optimal.

3. For the east atrium the minimum air change per hour was calculated to be 1 ACH when weather and wind conditions were poor. However a maximum air change per hour was calculated at 7.36 ACH when wind and weather conditions were optimal.

### 6.4 Effects of Roof Elements On 1:64 Detail Model

The fourth main objective of this study was to determine any flaws and shortcomings of the WTC roof system and to propose alternative roof methods. Studies relating to this were carried out initially on the 1:250 model and finally in greater detail on the 1:64 model. The following results and conclusions demonstrate the change on the roof system due to the inclusion of additional roof elements.

1. For the 1:64 model in its base case the roof system is least effective when winds are out of the east and west directions. The maximum ventilation efficiency for the roof systems occurs when winds are out of the northeast and northwest directions. At 4 mph the change in airflow at the interior of the atrium ranges from 14.60 fpm at the west position to 76.75 fpm at the north position. At 8 mph the change in airflow at the interior ranges from 32.64 fpm at the west position to 148.22 fpm at the north position.

2. For the 1:64 model with the wing element applied the roof system is least effective when the winds are out of the east and west directions. The maximum ventilation efficiency for the wing system occurs when winds are out of the northeast and southwest directions. At 4 mph the change in airflow at the interior of the atrium ranges from 16.06 fpm at the west

position to 85.97 fpm at the south position. At 8 mph the change in airflow at the interior range from 37.57 fpm at the east position to 180.99 fpm at the south position

3. For the 1:64 model with the wedge element applied the roof system is least effective when the winds are out of the east and west directions. The maximum ventilation efficiency for the wedge system occurs when winds are out of the northeast and southwest directions. At 4 mph the change in airflow at the interior of the atrium ranges from 19.85 fpm at the west position to 83.83 fpm at the south position. At 8 mph the change in airflow at the interior range from 37.14 fpm at the west position to 183.44 fpm at the south position

4. In conclusion both elements did little to enhance the performance of the roof system on the 1:64 model. It is highly likely that these elements would have worked better or more efficiently if a series of tests had been run to determine the optimum distance from the roof edge to the bottom of the element. As it stood during the test sequence of this study, the determination of the optimum distance would have required a great deal of time which was not available.

## 6.5 Optimum Wind Direction For Roof Elements

The final objective of this study was to determine if these alternative methods did indeed produce an increased performance and if so at which wind speed and at which wind direction. The following is the result of this study.

1. For the 1:64 model when the additional roof elements are in position the maximum ventilation efficiency is experienced when winds are out of the northeast and southeast. The maximum achieved airflow rate at 4 mph for these positions is 173.29 fpm for the wing and 185.74 fpm for the wedge. At 8 mph the maximum achieved airflow rate is 400.16 fpm for the wing and 415.19 fpm for the wedge element.

2. For the 1:64 model the wedge element performs slightly better than the wing element at the optimum wind directions (northeast and southeast) at both 4 mph and 8 mph.

## 6.6 Future Expansion of Study

Throughout the course of this study precautions were taken to prevent errors in the simulations and data streams. To limit errors in the data the data logger was left on continuously in order to retain the input program. This prevented calibration and data stream errors. To prevent errors on the models the transducers were moved as little as possible to prevent and accidental incidents, which may affect the calibration of the anemometers. Finally to limit error in the models a great deal of care and time was taken to ensure that the built test objects conformed in dimension to the provided digital documents.

While this project met it's objectives and provided a look into the principles of natural ventilation in use for large structures, there is room for expansion. In the case of this project and the test setup that was used there are two possible routes for expansion using the resulting data.

### 6.6.1 CFD Study

The first and most logistically feasible addition would be to take the World Trade Center and model it digitally in order to run CFD test and validate CFD as a viable design tool. Computation Fluid Dynamics yields similar results to the wind tunnel test but can do so at a higher rate of precision and autonomy. One of the largest drawbacks to the wind tunnel tests was the element of human error and interaction with turning the model or setting the transducers. In CFD's once the model was generated a whole host of test could be run using a program such as FLUENT to test for variations at the intake louvers or at the exhaust ports as well as variations due to thermal changes. Likewise one of the great benefits of using CFD's is the fact that the results from the computer simulations can be compared to the analog results of the wind tunnel tests. In all cases the use of CFD does seem to be the next logical progression in this study and could be done in a relatively short amount of time and at a low expense.

### 6.6.2 In-situ Monitoring

The second and more ambitious step would be to run data at the real site in Amsterdam. In the ideal set up air flow transducers would be installed on the actual building, when completed, and would record changes in the air speed in relation to the weather conditions on site. As the data and weather conditions are logged the information would then be sent electronically to a computer in Blacksburg that would mechanically orient the model in the wind tunnel and vary the speed of the wind to match the present conditions in situ. Next data readings would be taken at corresponding transducers set up on the model and would then be compared with the incoming data. The final step to this would also have a computer program set up that would feed live weather conditions for the WTC in Amsterdam into a CFD program that would also model the complex in comparison to real world conditions. This of course is quite ambitious and would most likely lay down the groundwork for a dissertation study.

## 6.7 Conclusion

Throughout this entire study the overriding objective was form a better understanding of the basic principles of natural ventilation and how they applied to large structures. For the purposes of this thesis the World Trade Center in Amsterdam was chosen as the test subject and was thus studied in great depth. While the principles at work at the WTC were scrutinized it was also the intention of this study to explore new methods and possibilities for improving on the proposed design by KPFI. Every objective set forth at the beginning of this project was met and it is the hope of this author that the information presented here will prove to be an insight to the natural ventilation possibilities in relation to large structures. On a larger scale it is also the hope and intention of this author that the presented work has served to simplify the methods of natural ventilation as well as to set the groundwork for future endeavors into the field of natural ventilation.

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## Appendix A: Provided Building Data

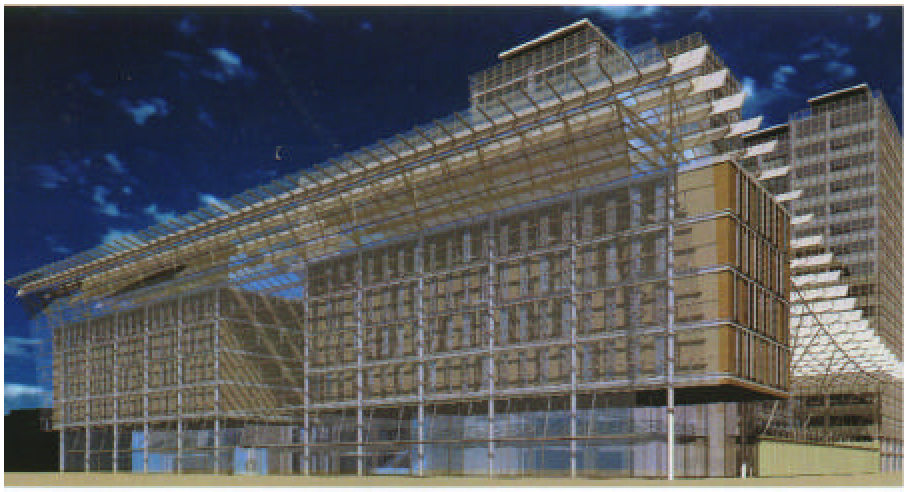

**Figure A.1. Rendering of WTC, Amsterdam (courtesy of KPFI)**

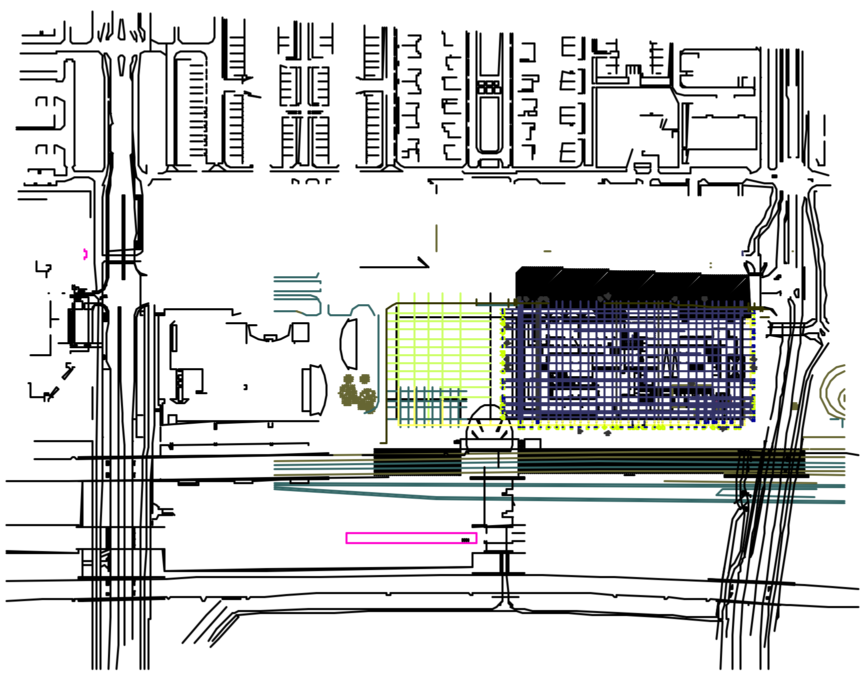

**Figure A.2. Site Plan of WTC, Zuidplien Area of Amsterdam (courtesy KPFI)**

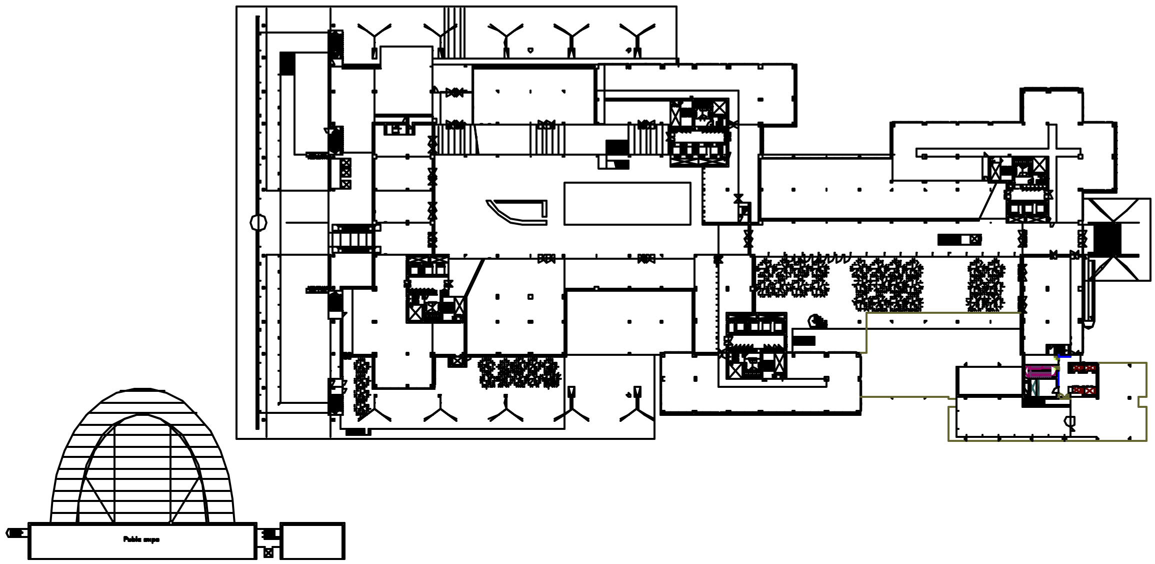

**Figure A.3. Second Floor Plan of WTC, not to scale (courtesy of KPFI)**

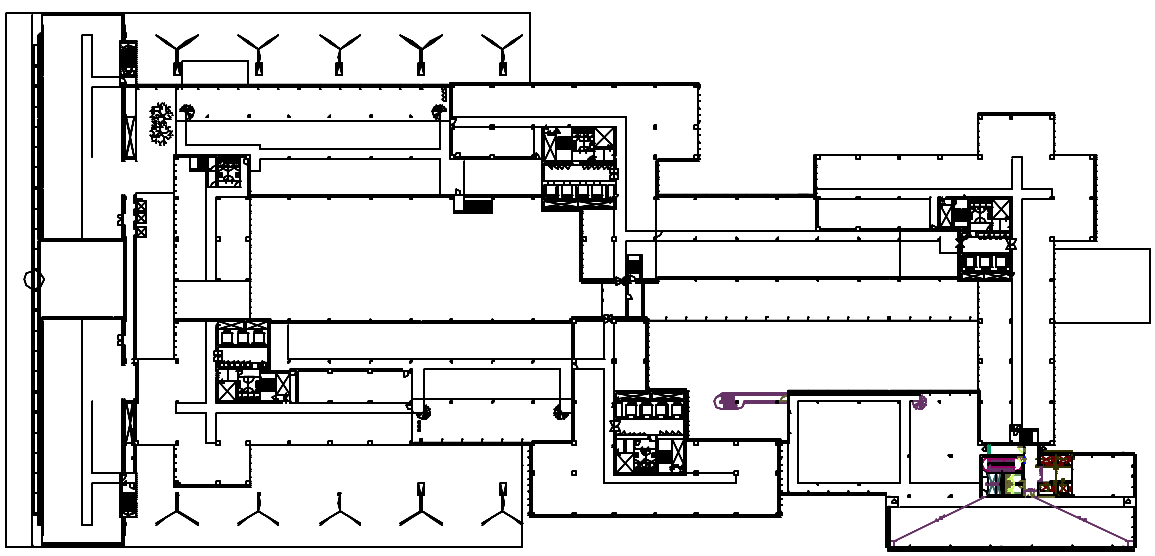

**Figure A.4. Third Floor Plan of WTC, not to scale (courtesy KPFI)**

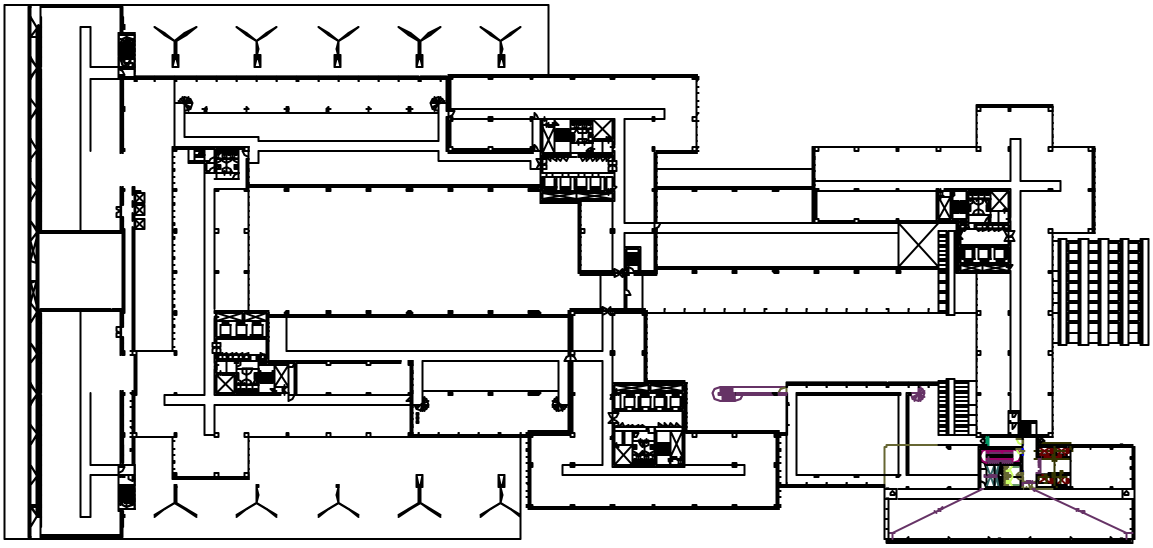

**Figure A.5. Fourth Floor Plan of WTC, not to scale (courtesy of KPFI)**

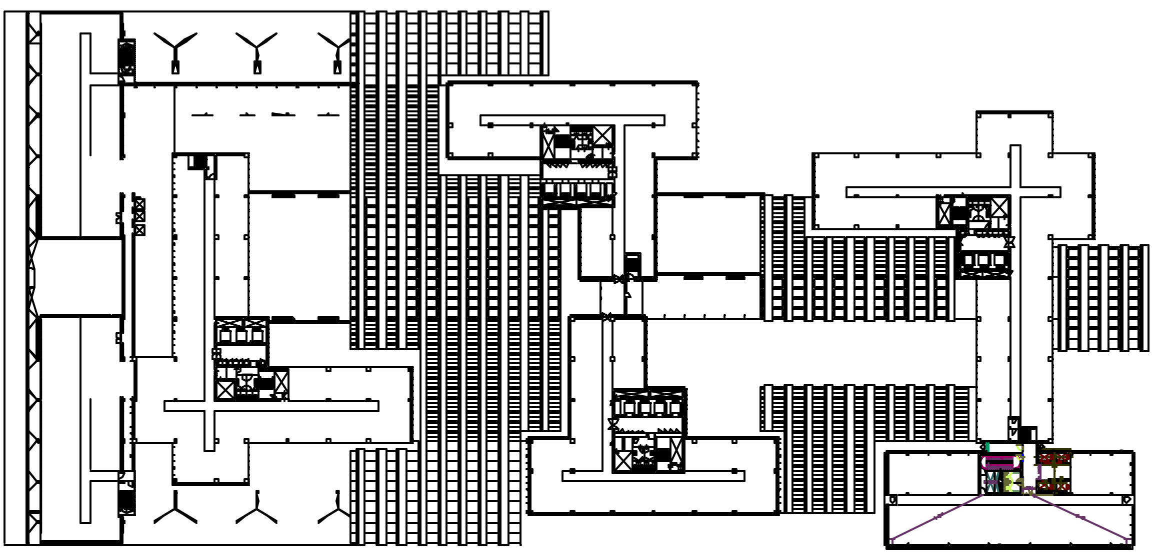

**Figure A.6. Fifth Floor Plan of WTC, not to scale (courtesy of KPFI)**

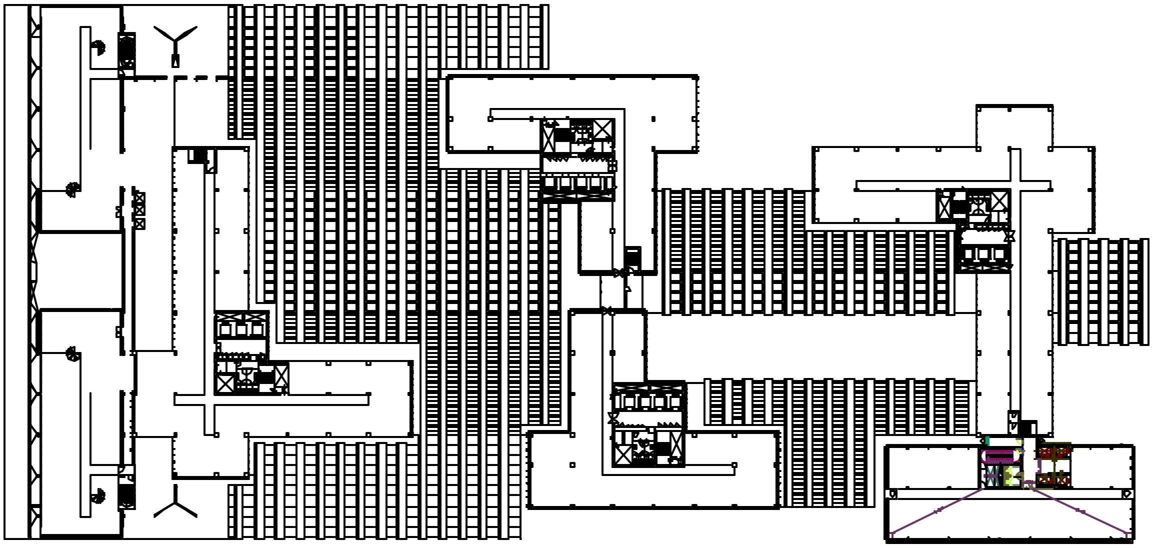

**Figure A.7. Sixth Floor Plan of WTC, not to scale (courtesy of KPFI)**

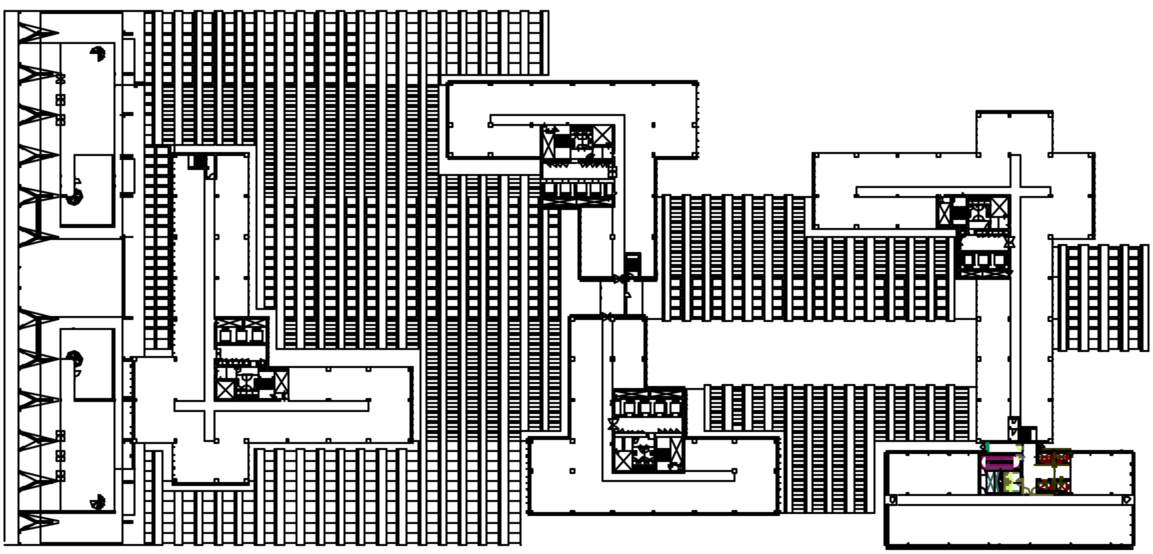

**Figure A.8. Seventh Floor Plan of WTC, not to scale (courtesy of KPFI)**

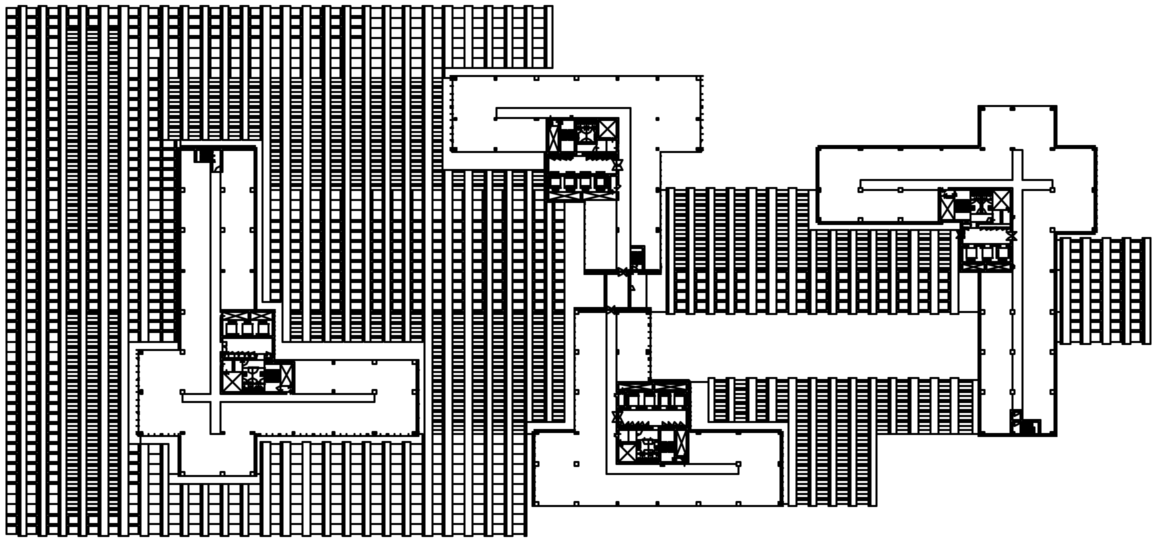

**Figure A.9. Roof Plan of WTC, not to scale (courtesy of KPFI)**

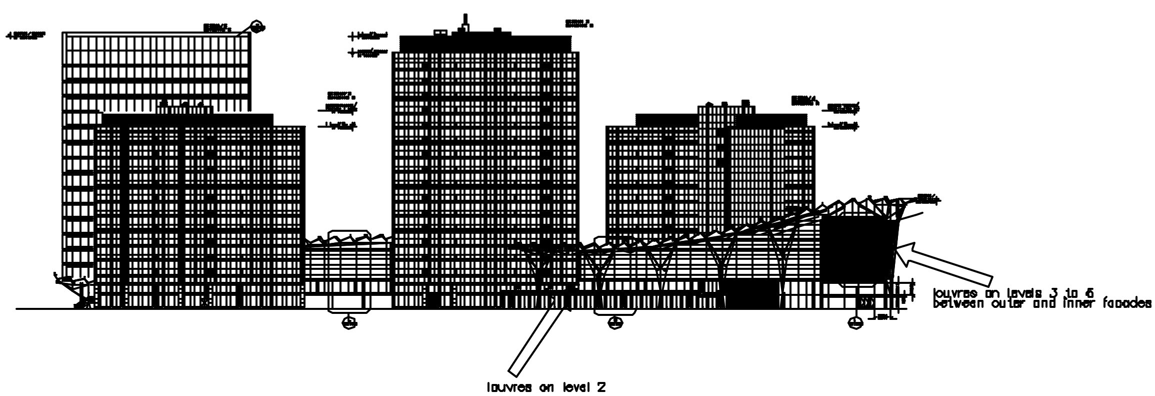


**Figure A.10. Elevation Showing Ventilation Intakes on WTC, not to scale (courtesy of KPFI)**

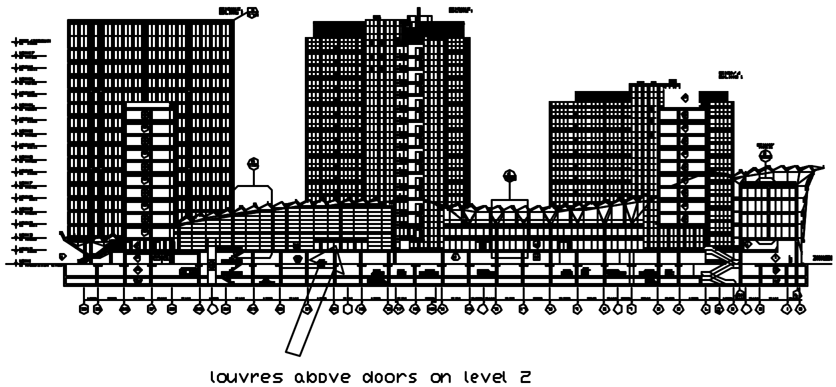


**Figure A.11. Section Showing Ventilation Intakes on WTC, not to scale (courtesy of KPFI)**

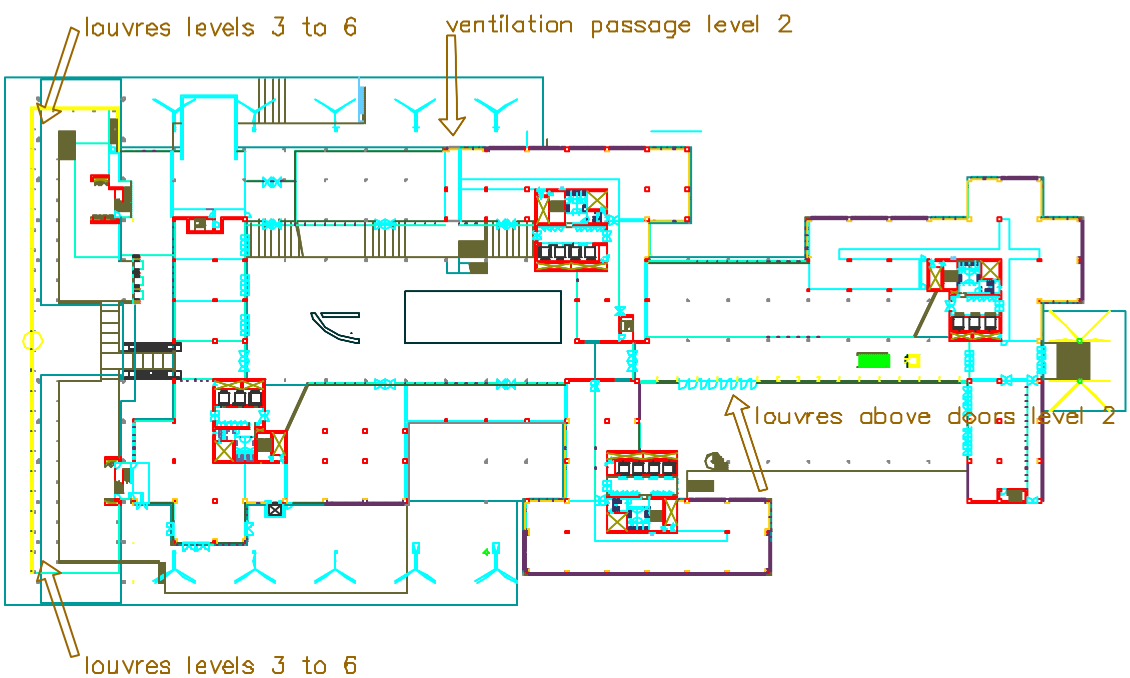


**Figure A.12. Floor Plan Showing Ventilation Intakes for WTC, not to scale (courtesy of KPFI)**

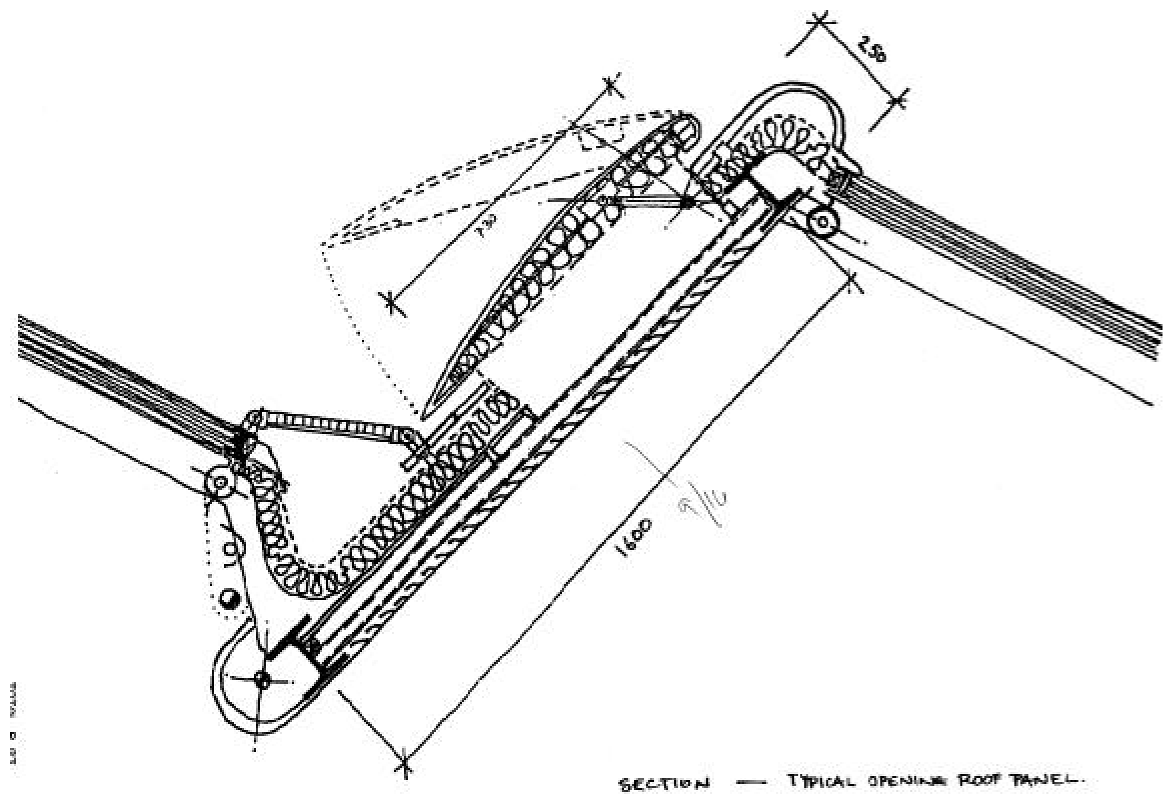


**Figure A.13. Section Showing Typical Louver Mechanism At Roof of WTC (courtesy of KPFI)**

## Appendix B: Samples of Data Tables

| | Position 1<br>W | Position 2<br>NW | Position 3<br>N | Position 4<br>NE | Position 5<br>E | Position 6<br>SE | Position 7<br>S | Position 8<br>SW |
|---|---|---|---|---|---|---|---|---|
| TSI-1 | 39.00 | 213.56 | 44.77 | 36.52 | 18.38 | 87.82 | 98.20 | 63.20 |
| TSI-2 | 18.00 | 49.23 | 8.77 | 16.43 | 14.59 | 41.08 | 39.47 | 61.46 |
| TSI-3 | 168.00 | 375.85 | 309.41 | 113.03 | 105.26 | 155.45 | 258.01 | 397.22 |

**Table B.1. Data values for west atrium, charts 5.1 through 5.3 (in fpm)**

| | Position 1<br>W | Position 2<br>NW | Position 3<br>N | Position 4<br>NE | Position 5<br>E | Position 6<br>SE | Position 7<br>S | Position 8<br>SW |
|---|---|---|---|---|---|---|---|---|
| TSI-1 | 32.00 | 213.10 | 210.70 | 126.62 | 121.09 | 68.45 | 80.94 | 57.85 |
| TSI-2 | 18.00 | 87.08 | 151.35 | 114.48 | 89.75 | 42.27 | 49.26 | 34.43 |
| TSI-3 | 208.00 | 218.53 | 379.39 | 387.90 | 125.35 | 114.31 | 285.81 | 148.49 |

**Table B.2. Data values for middle atrium, charts 5.4 through 5.6 (in fpm)**

| | Position 1<br>W | Position 2<br>NW | Position 3<br>N | Position 4<br>NE | Position 5<br>E | Position 6<br>SE | Position 7<br>S | Position 8<br>SW |
|---|---|---|---|---|---|---|---|---|
| TSI-1 | 27.00 | 203.61 | 214.57 | 167.28 | 51.11 | 54.54 | 34.95 | 34.72 |
| TSI-2 | 19.00 | 84.36 | 85.97 | 79.44 | 36.84 | 59.29 | 38.43 | 31.78 |
| TSI-3 | 85.00 | 161.44 | 255.32 | 175.97 | 160.54 | 175.98 | 280.99 | 334.57 |

**Table B.3. Data values for east atrium, charts 5.7 through 5.9 (in fpm)**

| Transducer | Air Flow Rate |
|---|---|
| TSI-1 East | 12.35 |
| TSI-2 East | 6.67 |
| TSI-3 East | 27.45 |
| TSI-1 Middle | 12.70 |
| TSI-2 Middle | 8.17 |
| TSI-3 Middle | 26.57 |
| TSI-1 West | 9.07 |
| TSI-2 West | 4.02 |
| TSI-3 West | 29.32 |

**Table B.4. Data values for chart 5.10 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 17.90 | 114.20 | 21.10 | 14.40 | 8.25 | 43.25 | 49.10 | 34.49 |
| **8 MPH** | 41.24 | 222.43 | 46.12 | 36.94 | 19.58 | 90.95 | 102.26 | 65.16 |
| **12 MPH** | 58.58 | 304.64 | 67.92 | 59.02 | 28.03 | 129.98 | 144.08 | 90.70 |

**Table B.5. Data values for west atrium inlet, chart 5.11 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 4.60 | 23.10 | 1.99 | 8.70 | 7.45 | 17.40 | 16.73 | 30.54 |
| **8 MPH** | 19.07 | 51.72 | 9.44 | 16.29 | 15.01 | 43.72 | 41.22 | 64.44 |
| **12 MPH** | 29.28 | 71.97 | 13.83 | 23.40 | 20.27 | 61.10 | 59.45 | 88.35 |

**Table B.6. Data values for west atrium interior, chart 5.12 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 78.8 | 170.5 | 150.7 | 48.04 | 3.21 | 63.4 | 119.33 | 196.48 |
| **8 MPH** | 173.80 | 414.79 | 313.32 | 116.66 | 65.48 | 158.73 | 263.93 | 443.73 |
| **12 MPH** | 250.55 | 523.23 | 463.31 | 173.45 | 112.22 | 243.32 | 390.18 | 550.51 |

**Table B.7. Data values for west atrium roof, chart 5.13 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 17.8 | 109.1 | 136.6 | 63.2 | 58.3 | 32.2 | 42.3 | 28.2 |
| **8 MPH** | 34.47 | 221.27 | 204.83 | 128.68 | 126.34 | 70.93 | 84.22 | 59.84 |
| **12 MPH** | 42.48 | 307.67 | 289.26 | 183.94 | 177.82 | 100.71 | 115.03 | 84.21 |

**Table B.8. Data values for middle atrium inlet, chart 5.14 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 8.4 | 46.4 | 92.5 | 57.5 | 49.2 | 22.9 | 27.1 | 15.3 |
| **8 MPH** | 20.17 | 91.62 | 150.86 | 119.33 | 92.69 | 43.64 | 51.73 | 36.66 |
| **12 MPH** | 26.77 | 124.76 | 212.26 | 165.62 | 129.25 | 61.42 | 70.24 | 52.89 |

**Table B.9. Data values for middle atrium interior, chart 5.15 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 110.2 | 102.6 | 242.5 | 194.4 | 59.6 | 49.2 | 148.3 | 74.2 |
| **8 MPH** | 217.24 | 226.59 | 372.16 | 408.47 | 132.97 | 117.05 | 290.67 | 155.17 |
| **12 MPH** | 295.36 | 325.29 | 522.31 | 551.21 | 182.89 | 175.36 | 417.33 | 214.82 |

**Table B.10. Data values for middle atrium roof, chart 5.16 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 13.90 | 98.10 | 103.30 | 81.10 | 21.60 | 26.60 | 12.40 | 16.90 |
| **8 MPH** | 27.61 | 211.28 | 225.52 | 173.99 | 48.97 | 52.67 | 36.21 | 34.44 |
| **12 MPH** | 38.38 | 300.39 | 313.61 | 241.90 | 81.52 | 83.30 | 55.15 | 51.77 |

**Table B.11. Data values for east atrium inlet, chart 5.17 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 7.30 | 44.60 | 42.70 | 43.60 | 15.80 | 30.30 | 15.10 | 12.70 |
| **8 MPH** | 20.43 | 87.07 | 88.93 | 82.31 | 36.31 | 59.58 | 39.16 | 32.66 |
| **12 MPH** | 28.63 | 120.61 | 125.69 | 110.12 | 57.67 | 87.22 | 60.38 | 49.27 |

**Table B.12 Data values for east atrium interior, chart 5.18 (in fpm)**

| | Pos. 1 (W) | Pos. 2 (NW) | Pos. 3 (N) | Pos. 4 (NE) | Pos. 5 (E) | Pos. 6 (SE) | Pos. 7 (S) | Pos. 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **4 MPH** | 37.30 | 68.70 | 113.10 | 81.00 | 72.90 | 78.60 | 137.10 | 142.60 |
| **8 MPH** | 86.77 | 169.17 | 262.55 | 181.82 | 156.73 | 181.58 | 284.07 | 341.83 |
| **12 MPH** | 130.41 | 246.26 | 390.08 | 260.79 | 251.62 | 267.64 | 421.62 | 519.23 |

**Table B.13. Data values for east atrium roof, chart 5.19 (in fpm)**

| | Position 1 (W) | Position 2 (NW) | Position 3 (N) | Position 4 (NE) | Position 5 (E) | Position 6 (SE) | Position 7 (S) | Position 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **Base** | 69.96 | 260.69 | 256.28 | 282.84 | 58.36 | 116.27 | 121.61 | 132.00 |
| **Wing** | 76.96 | 214.31 | 208.91 | 256.77 | 54.88 | 122.02 | 126.85 | 130.02 |
| **Wedge** | 92.23 | 233.49 | 236.93 | 260.84 | 65.80 | 136.08 | 135.00 | 147.34 |

**Table B.14. Data values for 1:64 model inlet at 4 mph, chart 5.20 (in fpm)**

| | Position 1 (W) | Position 2 (NW) | Position 3 (N) | Position 4 (NE) | Position 5 (E) | Position 6 (SE) | Position 7 (S) | Position 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **Base** | 14.60 | 61.47 | 76.75 | 42.23 | 52.86 | 42.16 | 73.55 | 67.09 |
| **Wing** | 16.06 | 46.67 | 65.16 | 55.21 | 17.58 | 54.23 | 85.97 | 38.15 |
| **Wedge** | 19.85 | 51.05 | 61.20 | 55.54 | 23.50 | 60.80 | 83.83 | 39.64 |

**Table B.15. Data values for 1:64 model interior at 4 mph, chart 5.21 (in fpm)**

| | Position 1 (W) | Position 2 (NW) | Position 3 (N) | Position 4 (NE) | Position 5 (E) | Position 6 (SE) | Position 7 (S) | Position 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **Base** | 70.04 | 146.41 | 158.06 | 84.70 | 133.02 | 119.78 | 143.65 | 147.82 |
| **Wing** | 86.58 | 142.31 | 91.62 | 173.29 | 75.20 | 98.58 | 123.37 | 156.18 |
| **Wedge** | 88.91 | 118.35 | 180.43 | 185.74 | 126.31 | 100.97 | 127.63 | 141.51 |

**Table B.16. Data values for 1:64 model roof at 4 mph, chart 5.22 (in fpm)**

| | Position 1 (W) | Position 2 (NW) | Position 3 (N) | Position 4 (NE) | Position 5 (E) | Position 6 (SE) | Position 7 (S) | Position 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **Base** | 143.36 | 529.91 | 496.18 | 541.74 | 128.93 | 248.20 | 250.78 | 272.50 |
| **Wing** | 159.87 | 452.54 | 418.17 | 512.70 | 125.42 | 255.41 | 251.65 | 253.62 |
| **Wedge** | 179.23 | 484.96 | 453.08 | 512.96 | 138.82 | 288.19 | 270.76 | 289.85 |

**Table B.17. Data values for 1:64 model inlet at 8 mph, chart 5.23 (in fpm)**

| | Position 1 (W) | Position 2 (NW) | Position 3 (N) | Position 4 (NE) | Position 5 (E) | Position 6 (SE) | Position 7 (S) | Position 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **Base** | 32.64 | 123.88 | 148.11 | 80.95 | 106.21 | 80.70 | 143.97 | 141.11 |
| **Wing** | 42.44 | 90.53 | 124.41 | 107.05 | 37.57 | 84.54 | 180.99 | 94.85 |
| **Wedge** | 37.14 | 101.67 | 130.41 | 112.40 | 51.43 | 107.00 | 183.44 | 92.62 |

**Table B.18. Data values for 1:64 model interior at 8 mph, chart 5.24 (in fpm)**

| | Position 1 (W) | Position 2 (NW) | Position 3 (N) | Position 4 (NE) | Position 5 (E) | Position 6 (SE) | Position 7 (S) | Position 8 (SW) |
|---|---|---|---|---|---|---|---|---|
| **Base** | 141.96 | 301.18 | 342.30 | 234.77 | 267.45 | 290.81 | 303.90 | 289.90 |
| **Wing** | 158.99 | 298.73 | 197.64 | 400.60 | 164.00 | 215.30 | 258.49 | 298.79 |
| **Wedge** | 156.59 | 237.15 | 354.26 | 415.19 | 261.33 | 225.33 | 252.72 | 282.65 |

**Table B.19. Data values for 1:64 model roof at 8 mph, chart 5.25 (in fpm)**

## Appendix C: Model Images During Testing

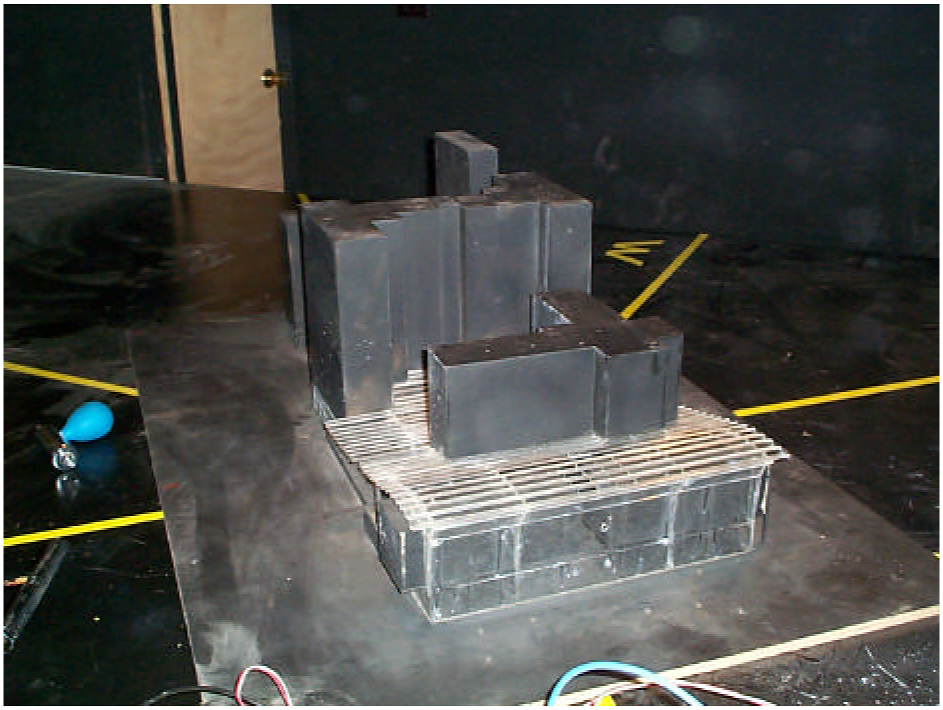

**Figure C.1. 1:250 Site Model During Visualization Tests**

**Figure C.2. 1:250 Model During Smoke Wand Tests on Middle Atrium**

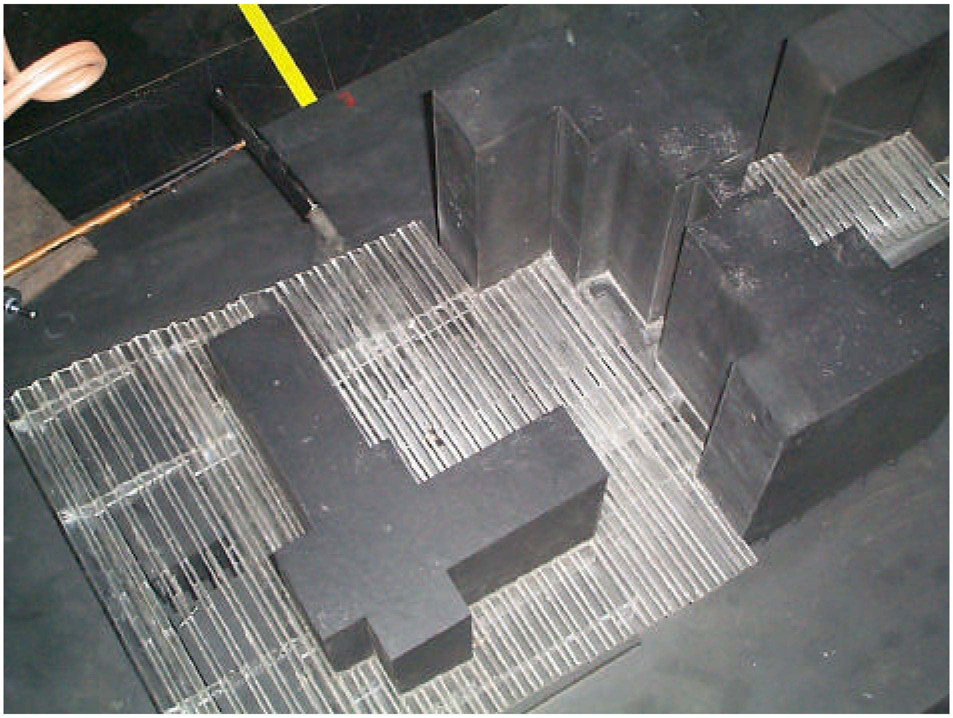

**Figure C.3. Top View of 1:250 Model During Smoke Wand Tests**

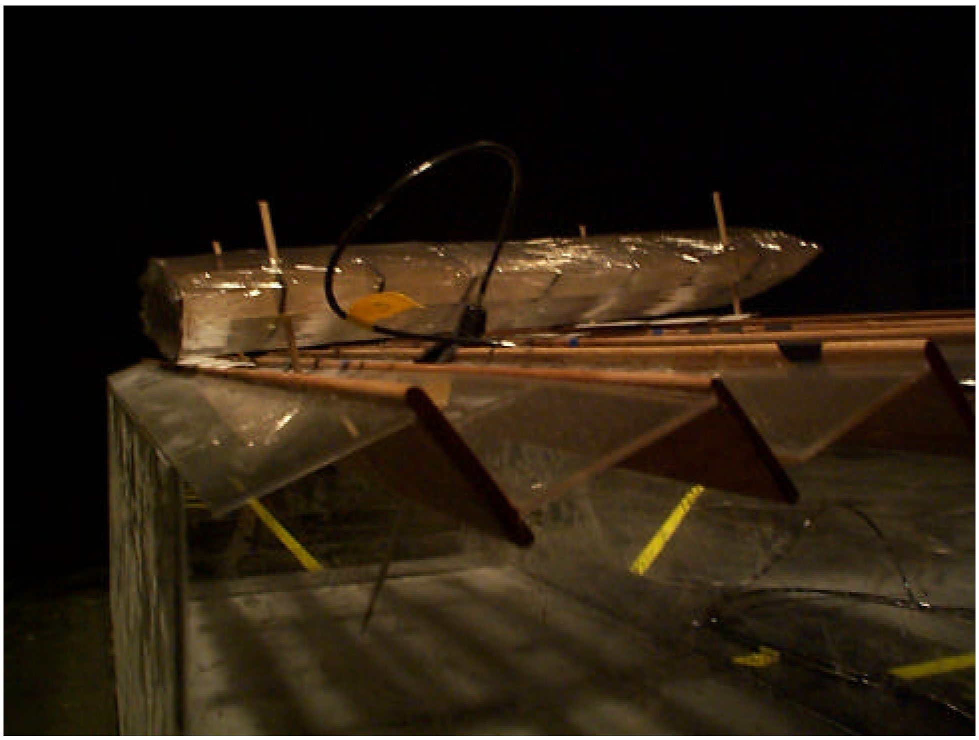

**Figure C.4. 1:64 Detail Model Showing Transducer Locations**

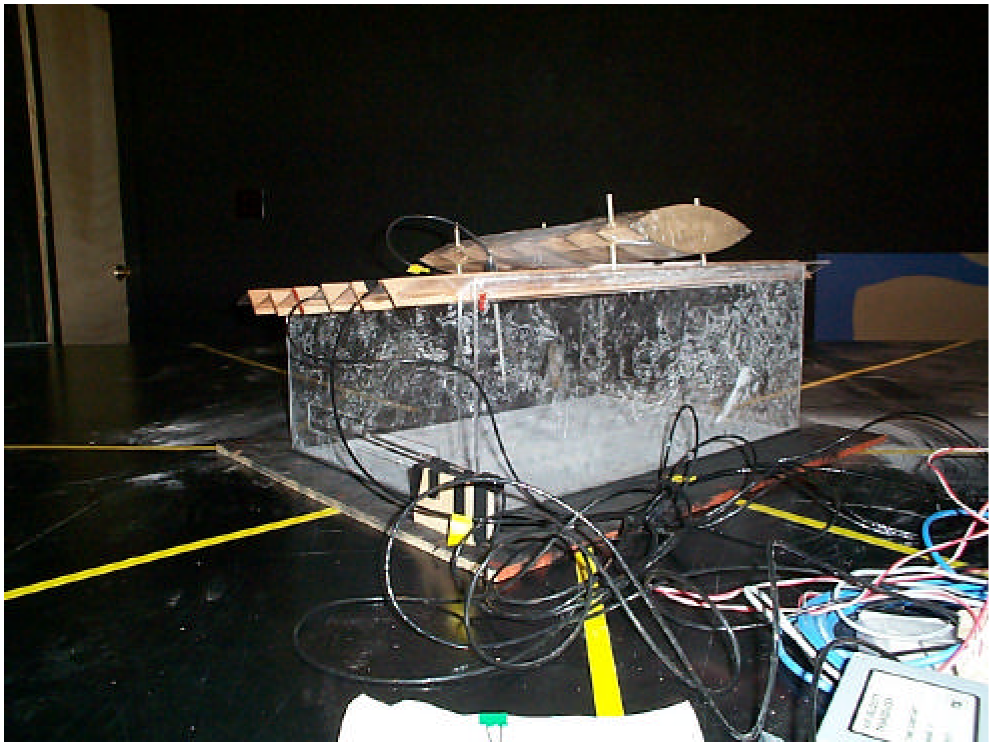

**Figure C.5. Detail Model During Zinc Powder Tests**

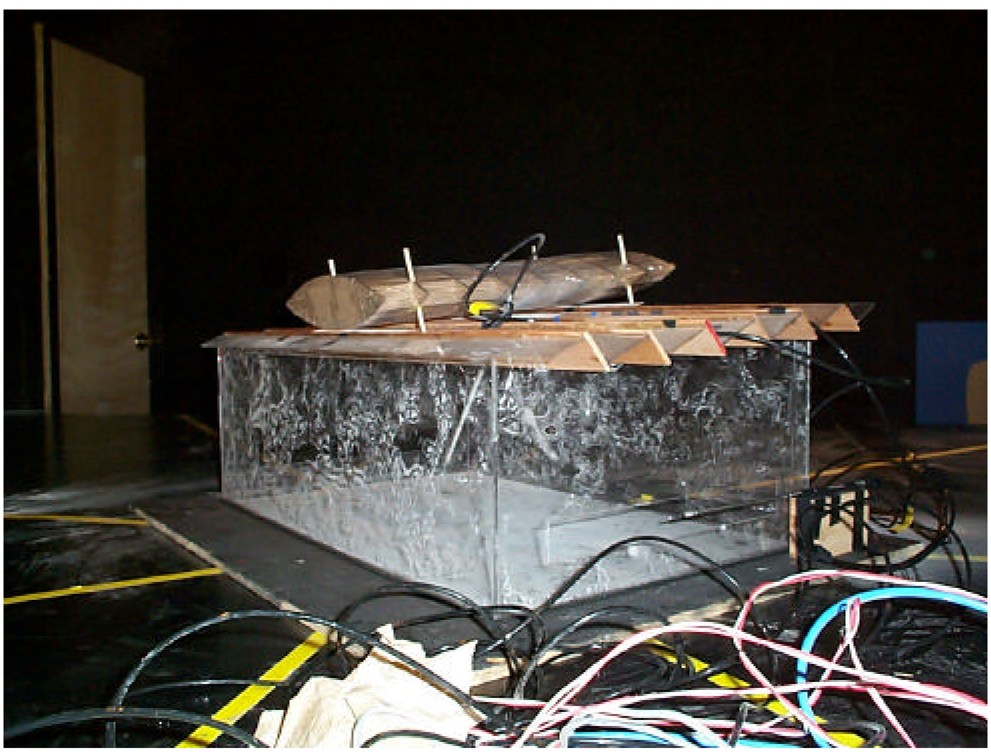

**Figure C.6. Side View of 1:64 Model During Zinc Powder Tests**

**Figure C.7. View of Wing Element in Action**

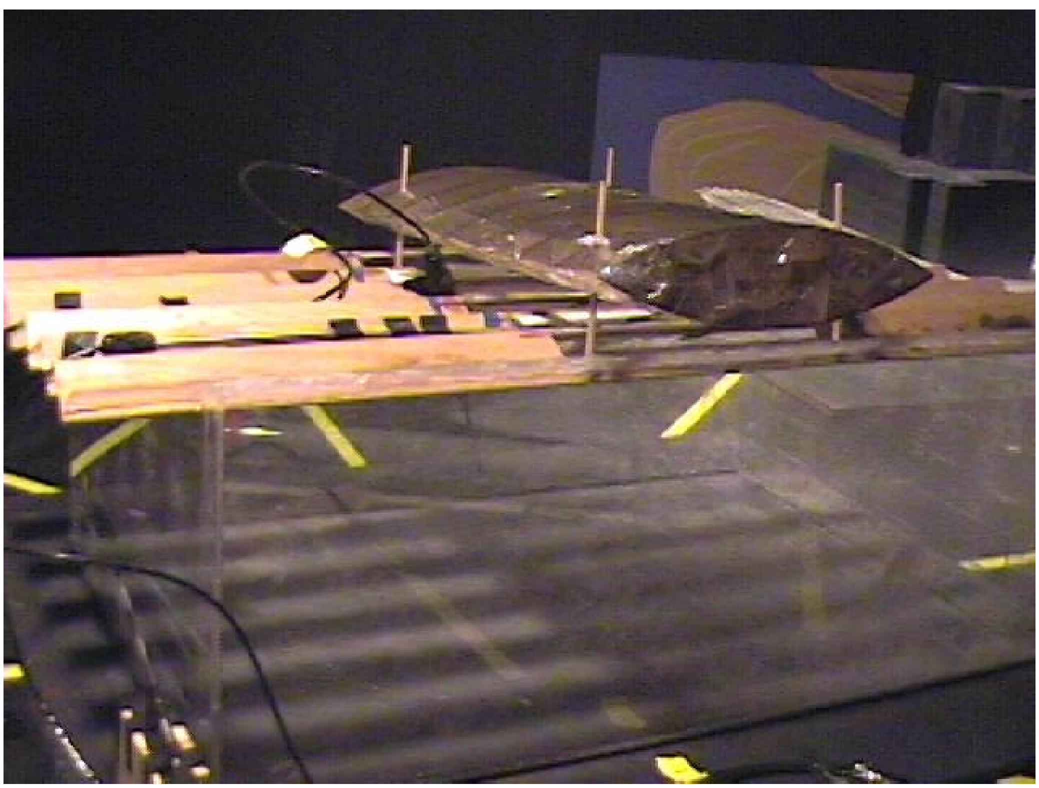

**Figure C.8. View of 1:64 Model Showing Element and Transducer Placement**

## Appendix D: Wind Tunnel Facilities

**Figure D.1. Environmental Science Laboratory at Virginia Tech**

**Figure D.2. Wind scoop at air intake of wind tunnel facility**

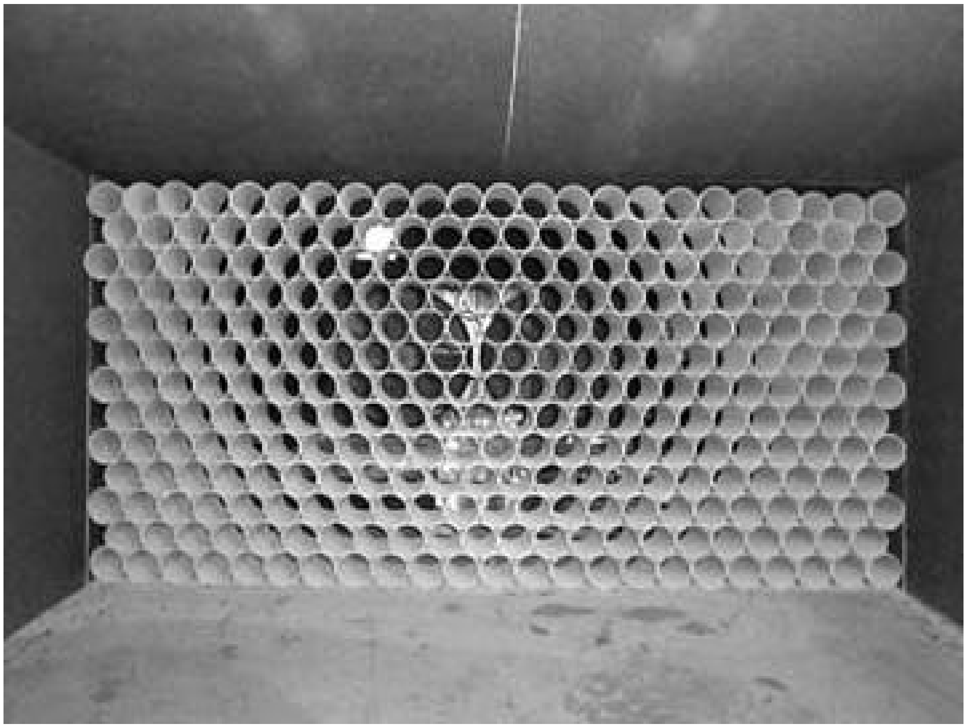

**Figure D.3. Air straighteners at air intake of wind tunnel**

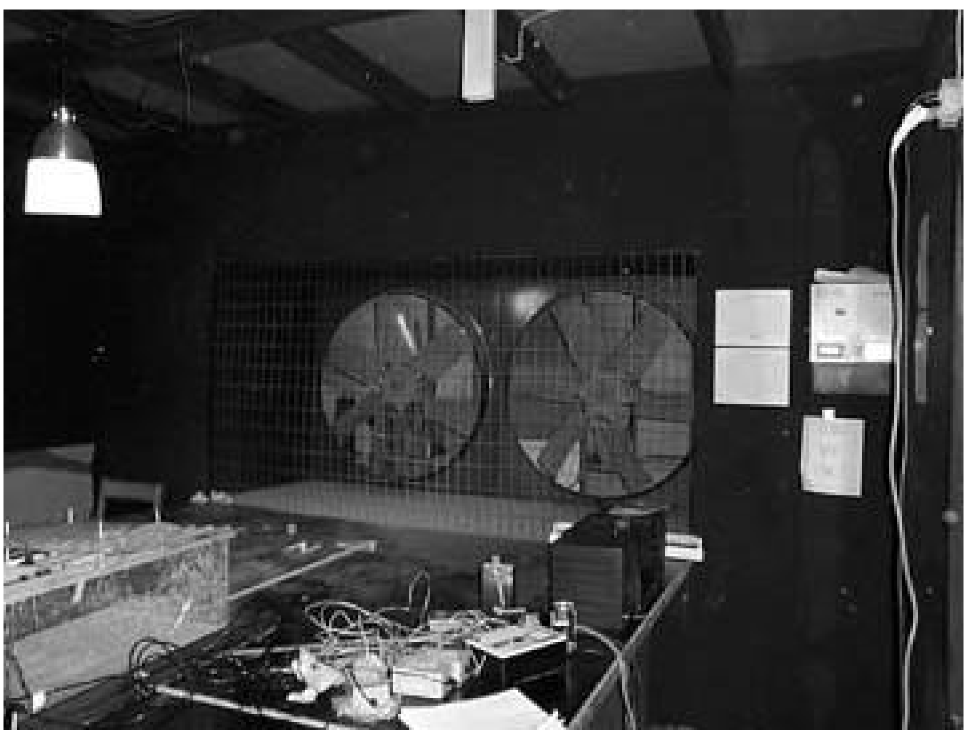

**Figure D.4. Interior of wind tunnel facility showing drive fans at back**


**Figure D.5. Toshiba ESP-130 transistor inverter speed controller**

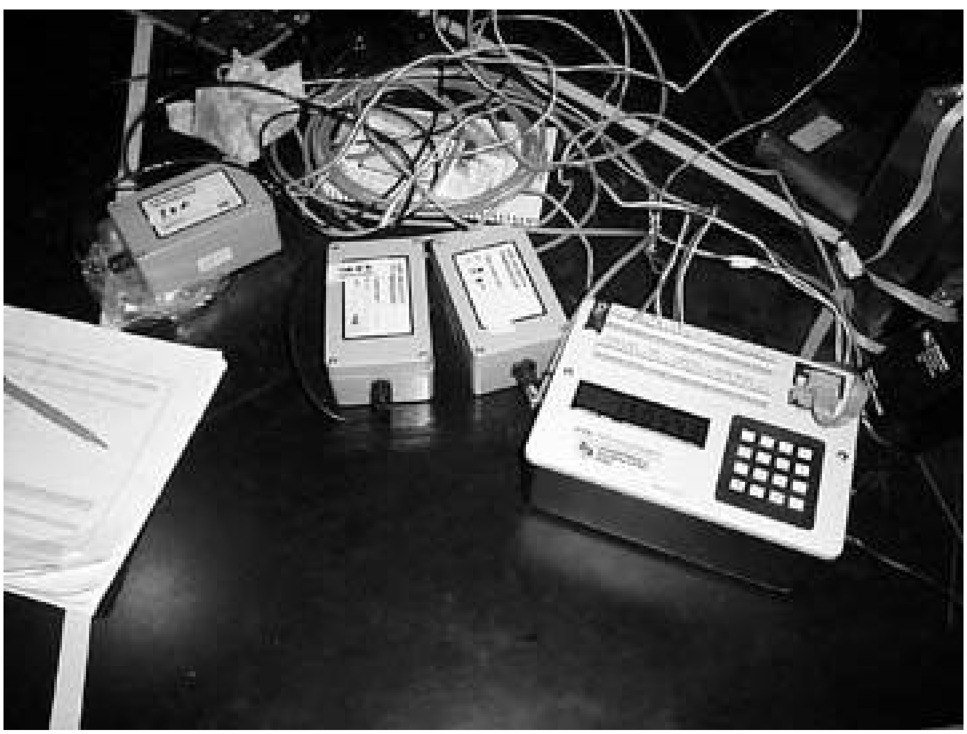

**Figure D.6. TSI airflow transducers and CSI 21X datalogger test setup**

## Vita

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*Coming Soon!!!!