ANALYSIS OF MIT CAMPUS WIND RESOURCES FOR FUTURE WIND TURBINE INSTALLATION

By

Brian E. Hack

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2008

Signature of Author: ________________________
Brian E. Hack
Department of Mechanical Engineering
May 9, 2008

Certified by: ________________________
Paul D. Sclavounos
Professor of Mechanical Engineering and Naval Architecture
Thesis Supervisor

Certified by: ________________________
Stephen R. Connors
Director, Analysis Group for Regional Energy Alternatives
Laboratory for Energy and the Environment, MIT Energy Initiative
Thesis Supervisor

Accepted by: ________________________
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

ANALYSIS OF MIT CAMPUS WIND RESOURCES
FOR FUTURE WIND TURBINE INSTALLATION

By

Brian E. Hack

Submitted to the Department of Mechanical Engineering
On May 9, 2008 in partial fulfillment of the
Requirements for the Degree of Bachelor of Science in
Mechanical Engineering

ABSTRACT

As our nation's continuing dependence on fossil energy and the problems that result from that dependence grow more apparent, we must look to alternative sources of energy to power the country. As a global scientific and technological leader, MIT is expected to take a part in the search for and support of alternative energy sources. One such source that has tremendous potential, yet tends to be underrepresented, is wind energy.

Following the previous wind resource analysis done by Richard Bates, Samantha Fox, Katherine McCusker, and Kathryn Pesce, I have expanded upon the suggestions made at the conclusion of their analysis. The Eastgate building on MIT's campus was identified as one possible location for small scale wind turbines. I completed a computational fluid dynamics (CFD) analysis on that building as well as the Johnson Athletic Center to determine if there were adequate wind resources to make the installation of a wind turbine on one of these buildings economical.

The results of the CFD analysis show that the west edge of the roof on the Johnson Athletic Center is a promising location for the installation of a roof-top wind turbine. Further investigation of the wind resources at that location should be conducted.

Thesis Supervisor: Paul D. Sclavounos
Title: Professor of Mechanical Engineering and Naval Architecture

TABLE OF CONTENTS

Section 1 – Introduction

It is undeniable that the world, and especially the United States, is in the midst of an energy crisis. With a consumption rate of 15 Terawatts of power worldwide and nearly ninety percent coming from fossil fuels[1] that contribute to global warming, a new approach to energy is needed. Current work is being done to build large-scale power plants that utilize renewable sources of energy. These plants, which largely replace coal-fired power plants, employ solar, wind or geothermal energy to create electricity. While power plants on the Megawatt scale are definitely a step in the right direction, more universal action is needed. There exist several wind turbine manufacturers that build models in the 1-3 Kilowatt range that are specifically designed for small installations on homes and other buildings.

The Massachusetts Institute of Technology has long been a leader in technology and seen as a role model for society. The MIT Energy Initiative was founded to advance research in the field of renewable energy with the goal of helping leaders in industry develop better products that provide clean energy[2]. One area of research that the MITEI has been involved in is small scale wind production. At its location in Cambridge, Massachusetts, MIT is not the ideal place to install a large MW wind turbine. There are very few, if any, places in the crowded city where a turbine of that magnitude could be installed and have enough wind resources to make it economical. With that in mind, architectural wind turbines, which are installed over the edges of building rooftops as seen in Figure 1, may be a way to incorporate wind energy into MIT's campus.

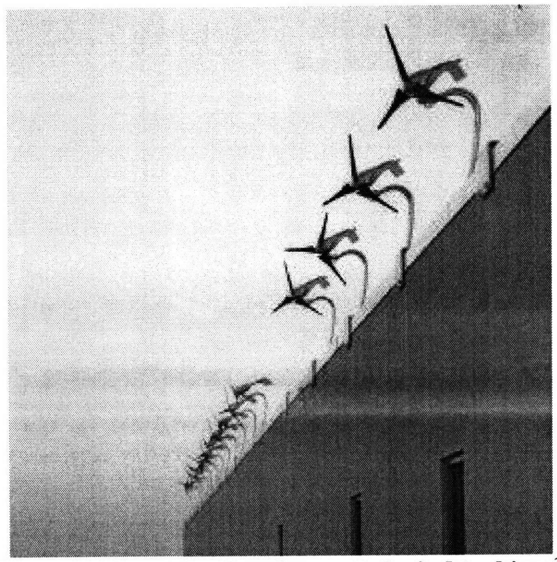

Figure 1. Example of roof-mounted wind turbines[3].

When a current of air encounters a solid structure in its way, it must find a way around that structure. The wind finds the shortest path, either around or over the building, and in the process speeds up. This phenomenon is a result of the Venturi effect, in which a moving fluid speeds up as it flows into a narrow region. As the wind accelerates over the edge of the roof, a region of high velocity wind is created, which becomes an ideal spot for electricity generation. In Figure 2, the lines represent streams of air as they encounter a building. When these streamlines flow over the top edge of the building, they become closer together, indicating an increase in velocity of the air stream.

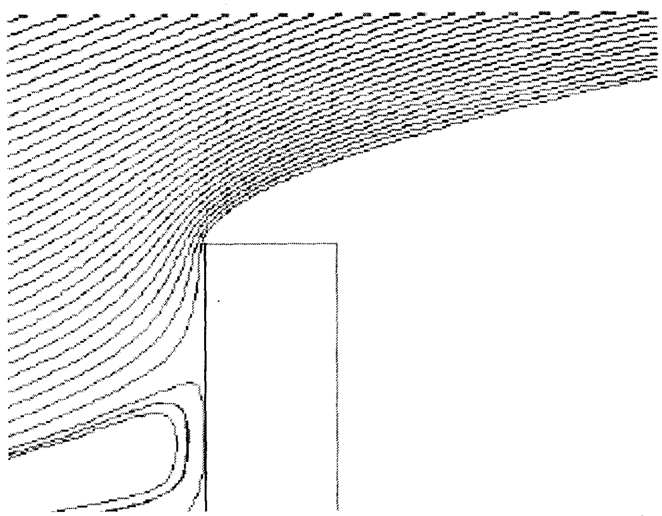

Figure 2. Diagram showing wind acceleration over edge of building[4].

Because of this effect, a smaller, more efficient turbine can operate in a region where a large wind turbine would be ineffective.

1. World Consumption of Primary Energy by Energy Type and Selected Country Groups.
2. "About MITEI."
3. AeroVironment, Inc.
4. Mertens, et. al

Section 2 - Prior Work

In the Spring of 2007, Richard Bates, Samantha Fox, Katherine McCusker, and Kathryn Pesce, under the guidance of Dan Wesolowski, completed a report titled "Wind Study: Feasibility Study and Recommendations for Implementing Wind Power on MIT's Campus." This study is a continuation of the work completed for that paper.

In the study done by Bates et.al., seven locations were chosen around MIT's campus and anemometers were placed on the buildings to record wind speed and direction. The research for this paper was to take one of the locations from the previous investigation, Eastgate graduate student dormitory, as well as another building, Johnson Athletic Center, and perform a computer-based wind simulation. Eastgate Dormitory was chosen because, at 90 meters[5], it is one of the tallest buildings on campus and situated close to the Charles River, meaning that the prevailing winds are unobstructed. Johnson Athletic Center is not a very tall building (only 22 meters)[6], but it is located next to a large athletic field, unobstructed by any other buildings. These simulations were completed using the data gathered in the previous paper regarding prevailing wind direction (205 degrees SSW), and average wind speed (4.9 meters per second, or 10.9 mph) for MIT's campus[7].

---

5. "Maps and Floorplans."
6. "Maps and Floorplans."
7. Bates, et.al.

Section 3 - Experimental Setup

While this study does not focus its attention on the physical collection of wind data, that information is used to create the computer simulations. I will briefly discuss the method for collecting the data. As shown in Figure 3 below, a stand with three anemometers was placed near the edge on the roof of Eastgate dormitory. The three anemometers are placed at heights of 5 feet, 9 feet, and 13 feet above the parapet[8].

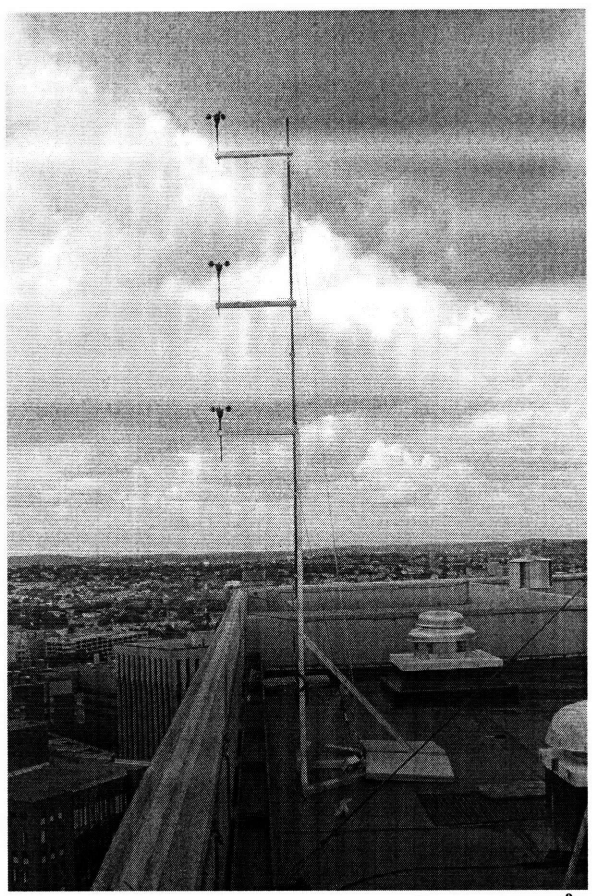

Figure 3. Setup of anemometers on Eastgate roof[9].

The anemometers sent wind speed information to HOBO micro station data loggers every 30 seconds, which was then collected with the HOBOware software, as seen in Figure 4.

The data, as shown in the figure, contains both wind speed over time, as well as gust speeds at discreet points in time.

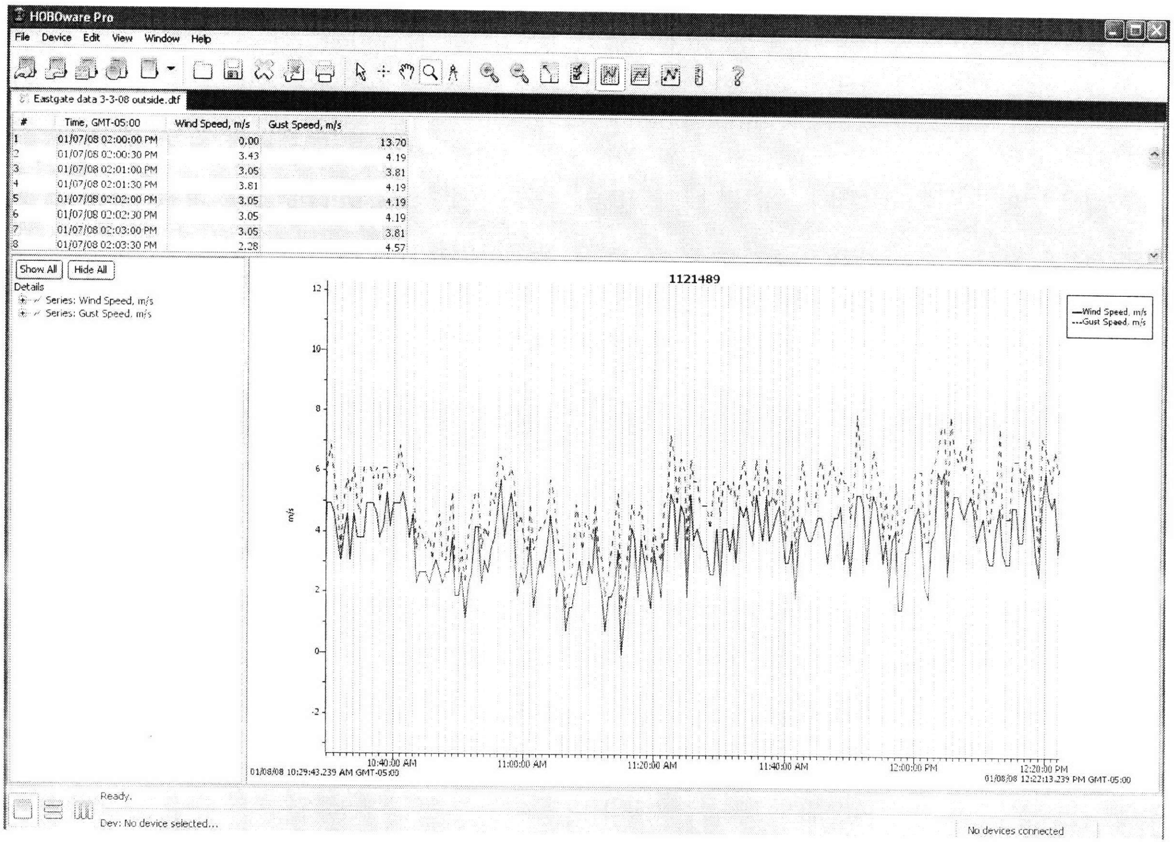

Figure 4. HOBOware data acquisition program.

The data collected from these anemometers were used to derive the average free-flow wind speed. Additionally, historic data from the Beverly Municipal Airport were used to determine average wind direction, shown in Figure 5. For further information about the derivation of free-flow wind speed and wind direction, please see Bates et. al, "Wind Study: Feasibility Study and Recommendations for Implementing Wind Power on MIT's Campus."

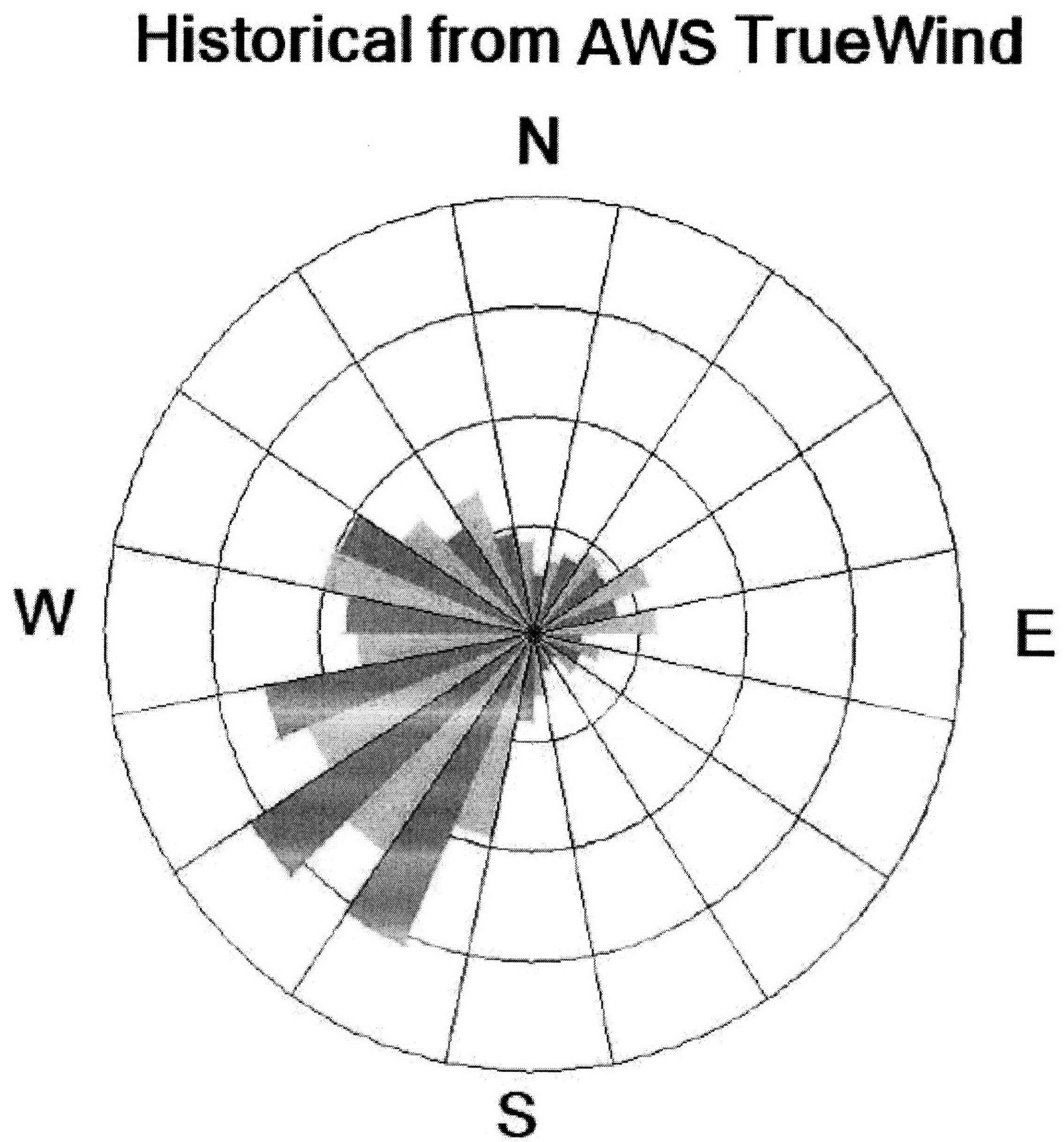

Figure 5. Historical predominant wind direction at Eastgate[10].

8. Bates, et.al.
9. Bates, et.al.
10. AWS TrueWind.

Section 4 - Model of wind flow generated by CFD program

The models in this study were created using a Computational Fluid Dynamics (CFD) program called PHOENICS. The name is an acronym that stands for *Parabolic Hyperbolic Or Elliptic Numerical Integration Code Series*[11]. CFD programs employ a numerical method for solving complex fluids dynamics problems. The equations that the program solves are based on the Navier-Stokes equation, shown in Figure 6.

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \mu\nabla^2\mathbf{v} + \mathbf{f} + (4\mu/3 + \mu^v)\nabla(\nabla\cdot\mathbf{v})$$

Figure 6. Navier-Stokes Equations employed by the CFD program.

Although the computer cannot solve the equations for a continuous fluid, an approximate solution is attained by breaking down all parts of the system to finite elements[12]. The moving air is made into many small particles, and the objects that the air particles interact with are broken down into a mesh of smaller parts. As the subdivisions become smaller and smaller, the results of the analysis become more accurate, but more processing power and time are required to do so.

PHOENICS has a graphical interface that lets the user build their environment, including the ground, sky, buildings and air inlets and outlets. Once the environment is created and the incoming wind flow is defined, the CFD program calculates the wind speed at every point in the environment. Another graphical interface displays the result of these calculations as colored vector fields representing various wind speeds.

11. "PHOENICS Overview."
12. "Introduction to Finite Element Analysis."

Section 4.1 – Eastgate wind model

The following model for Eastgate dormitory was made using the free wind speed of 4.9 m/s (10.9 mph) and wind direction of 205 degrees SSW. Figure 7 shows a profile of the building with arrows indicating wind direction, and a colored gradient indicating wind speed. The incident stream of air is coming in from the left side of the picture, and the region of highest wind speed is approximately 15 meters above the back edge of the roof.

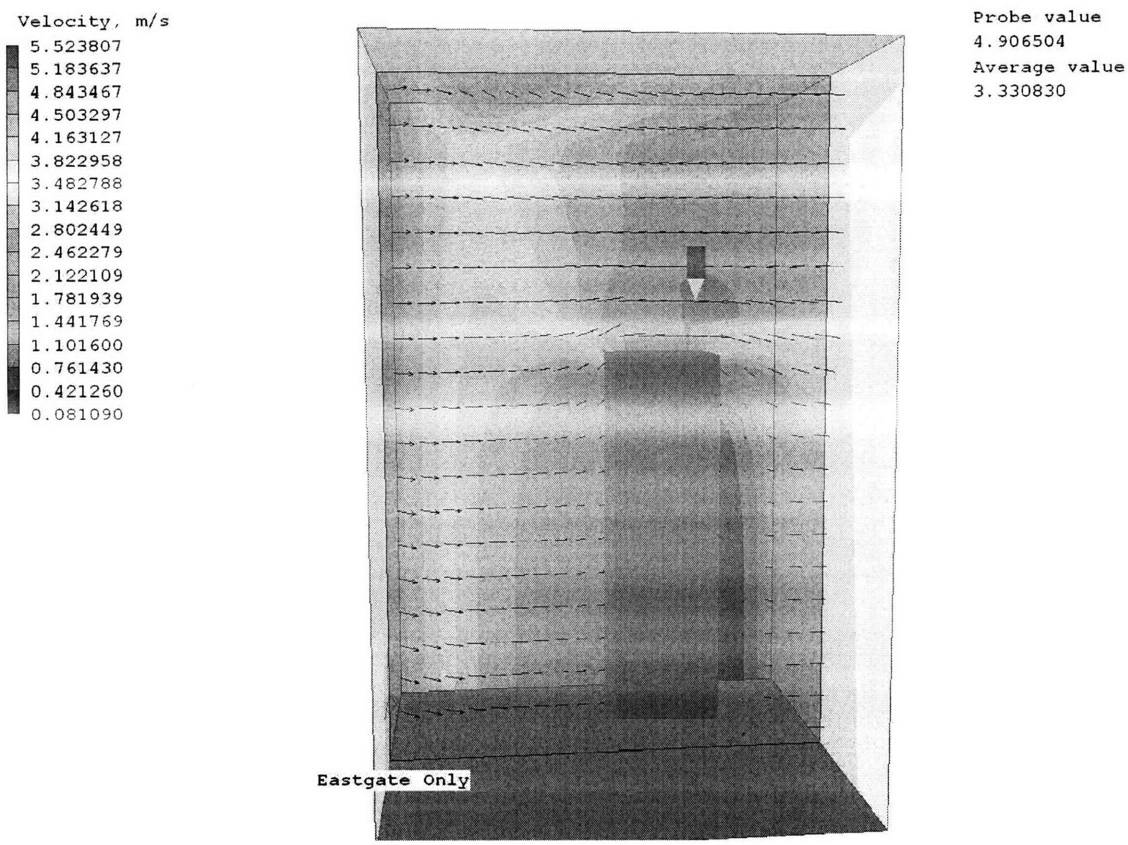

Figure 7. Wind velocity profile around Eastgate.

In the following picture, Figure 8, a solid region of the maximum wind speed is defined. The model clearly shows that there is an increase in the velocity of air as it flows around the building due to the Venturi effect described above. The maximum wind speed given in the model is 5.5 m/s, a 13% increase over the incident wind speed of 4.9 m/s.

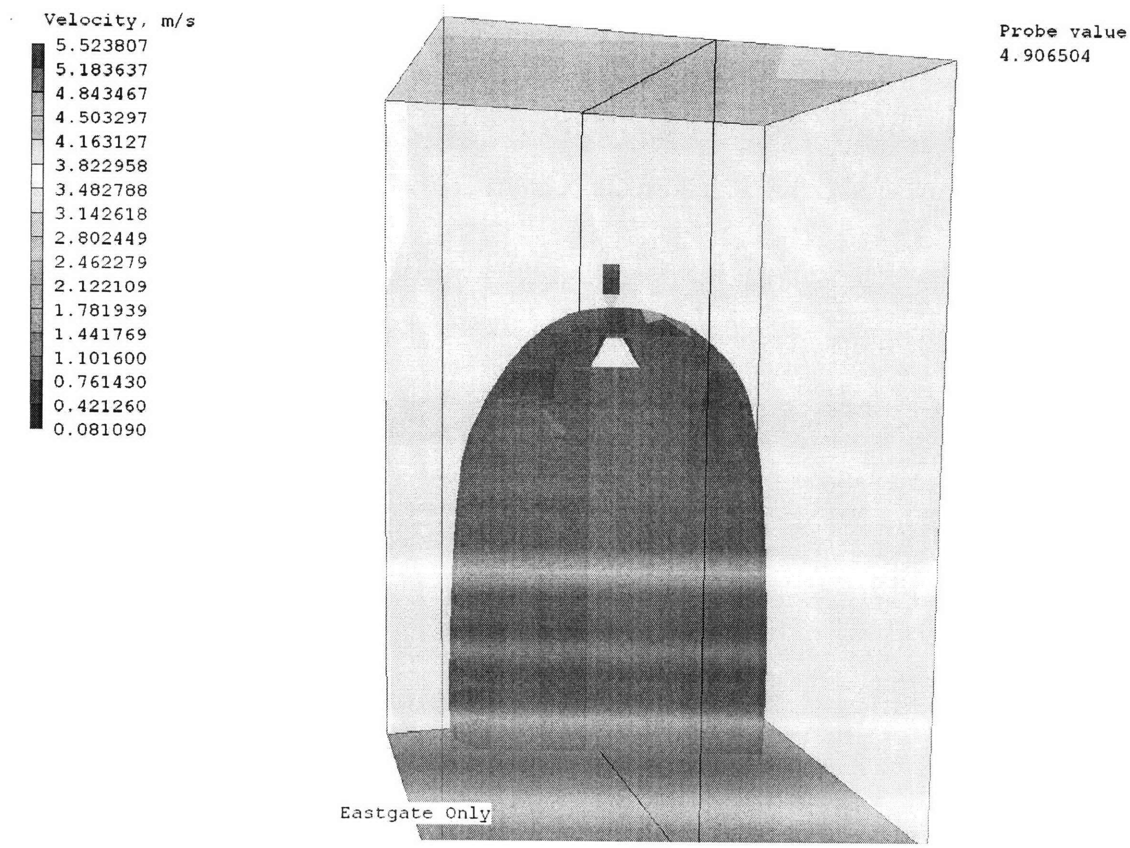

Figure 8. Region of peak wind velocity surrounding Eastgate.

A more complete model of Eastgate dormitory was also made, including several of the surrounding buildings that might have had an effect on the wind speed profile of Eastgate. As can be seen in Figure 9, the other buildings in this model decrease the size of the region of maximum wind velocity on the side of Eastgate. However, there is no appreciable effect on the region of maximum wind velocity on the roof.

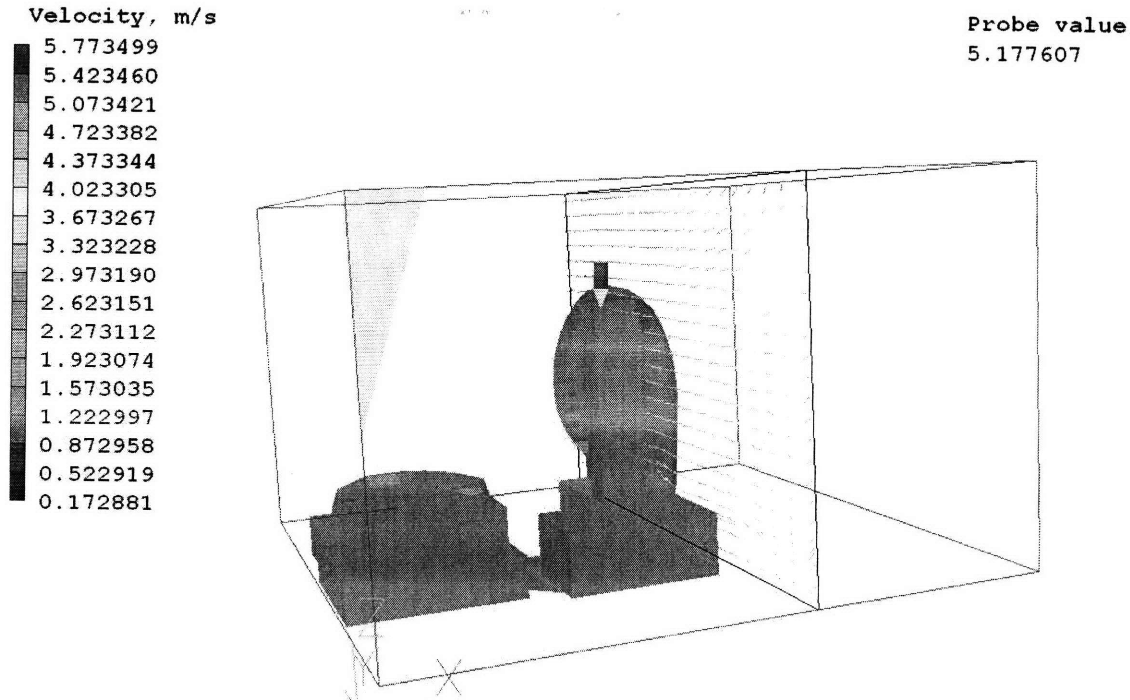

Figure 9. Region of peak wind velocity surrounding Eastgate influenced by surrounding buildings.

One point of concern from this model is the fact that the region of maximum wind velocity does not occur directly at the edge of the building. In fact, that region occurs 15 meters above the roof and far away from the edge where wind is flowing over. Also, the roof of Eastgate is not completely flat, as is shown in this model. The more complicated geometry could potentially interrupt the region of high wind velocity. Because of these two factors, the roof of Eastgate does not seem like a place where an edge-mounted architectural wind turbine could be practically installed.

Section 4.2 – Johnson wind model

The second building for which a CFD model was made is Johnson Athletic Center. This building was chosen for its location next to the athletic fields. As shown in Figure 10, the building faces directly over the football field and track, with several hundred more meters of open field beyond that. That means that there are about three hundred meters of uninterrupted air flow before the wind hits the building.

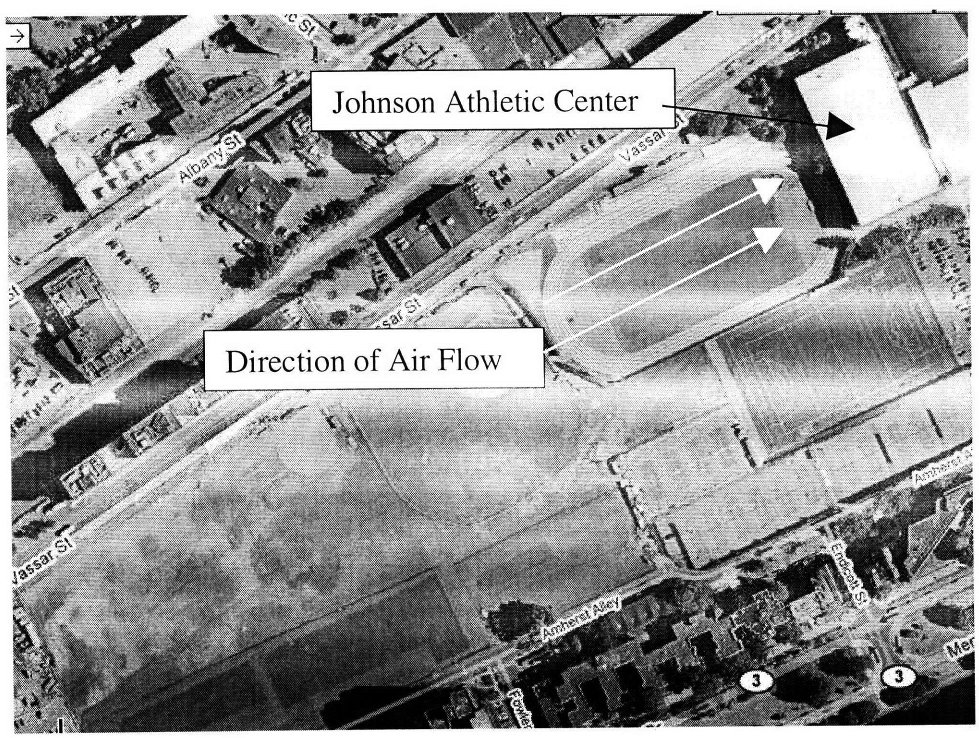

Figure 10. Overhead view of Johnson Athletic Center and surrounding area[13].

The CFD model was built with the assumptions that the wind hits the edge of the building perpendicular to the face at the previously calculated speed of 4.9 meters per second. Figure 11 shows the results of running that model through the simulation.

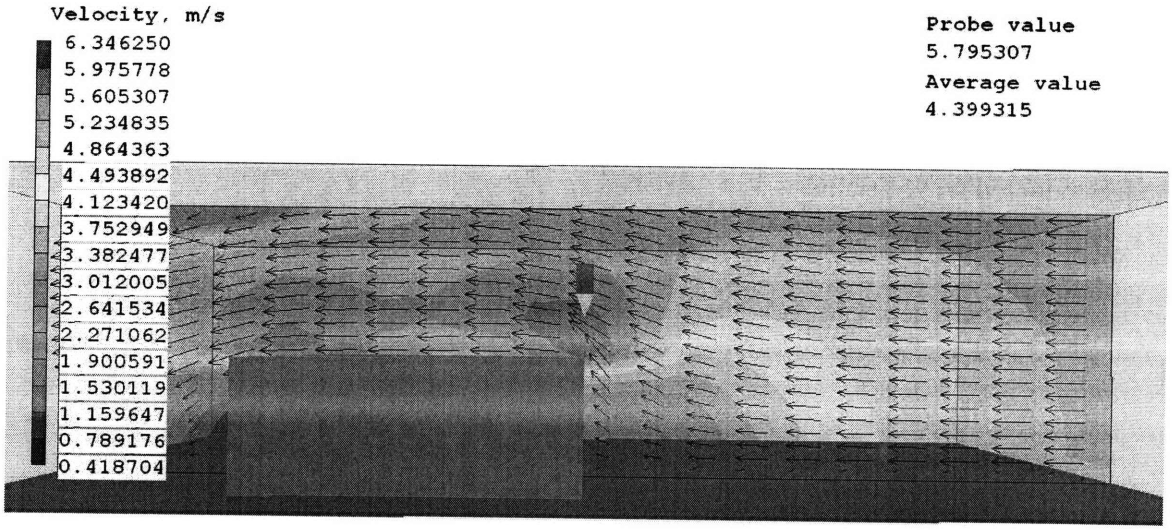

Figure 11. Wind velocity profile around Johnson Athletic Center.

As seen in the above figure, the wind comes from the right hand side and impacts the building, forcing it up and over the front edge. The red, egg-shaped region in the picture represents a wind speed of 6.3 meters per second, or a 29% increase in wind speed. Figure 12, below, shows the solid region of the maximum wind velocity.

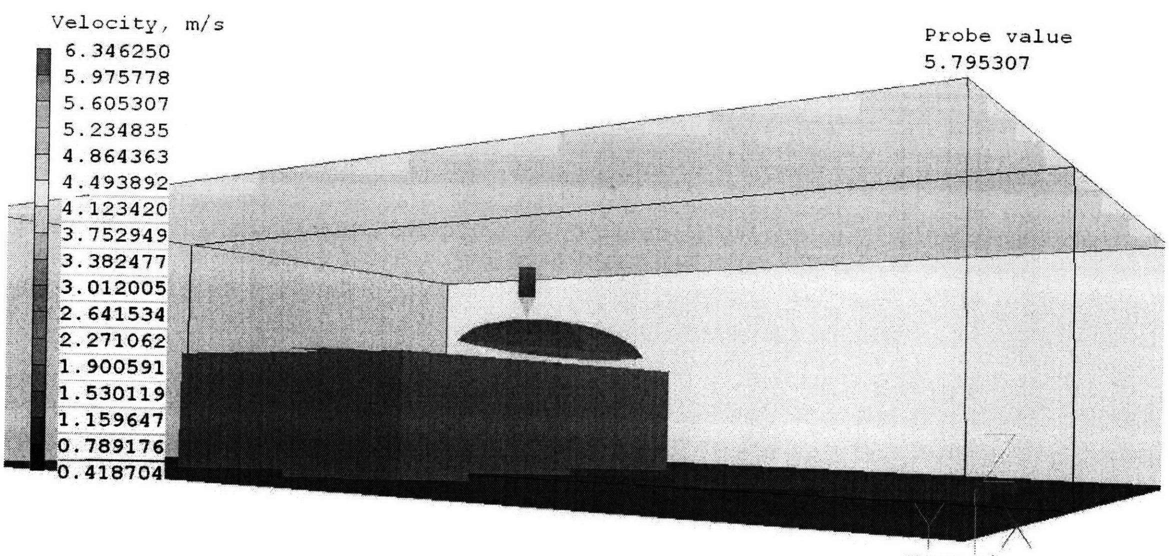

Figure 12. Region of peak wind velocity surrounding Johnson Athletic Center.

The results of this simulation are very promising. There is a large increase in the velocity of the incident wind, and the region of maximum wind speed is at the edge of the building, approximately 5 meters above the roof. It seems that despite a lack of height, Johnson Athletic Center, standing at just over 22 meters, makes a great candidate for a building edge-mounted wind turbine.

A possible explanation for the larger increase in wind velocity at Johnson over Eastgate is the difference in geometry of the two buildings. The high wind velocity region around Eastgate was not just at the roof of the building, but also vertically along the sides. Because Johnson is much shorter compared to its width, the wind is more likely to be accelerated up and over the top of the building rather than around the sides as was the case at Eastgate.

---

13. Google Maps

Section 5 – Results and Suggestions for Future Work

The results of the CFD analysis of this study have proven useful in defining the next step that MIT can take towards the ultimate goal of installing a wind turbine on campus. While that goal is not immediately achievable, we are closer to finding a suitable place to install a building rooftop wind turbine. As a next step, I suggest that anemometers be installed on the west edge of the roof of Johnson Athletic Center at a height of 5 meters. For a more complete picture of the wind profile, an array of anemometers located at different heights and at different points along the edge of the roof should be installed.

There is high potential for the application of small scale wind energy collection systems on MIT's campus. The Johnson Athletic Center consumes approximately 250 kW of power[14], equaling over two million kWhr per year, while a Skystream 3.7 has an annual energy output of 3761 kWh, assuming a 15% capacity factor[15]. In order to fully offset the energy use of Johnson Athletic Center, hundreds of small wind turbines would be needed. Despite this high number, an installation would still help to offset energy usage, while making a statement about MIT's commitment to renewable sources of energy.

I encourage MIT to continue to pursue this endeavor. Installing a wind turbine on top of a building would provide a great opportunity to learn more about the dynamics of small-scale wind turbines and what can be done with smaller wind resources that are not suitable for larger turbines. The whole world is watching what is done here, and we need to set a good example for others to follow.

14. "MIT Campus Energy Use."
15. "Post Report Analysis."

Section 6 – Acknowledgements

I would like to thank Stephen Connors and Dan Wesolowski for all of the help that they have provided me during the course of this research project. I would also like to thank Beth Conlin, Les Norford, Leon Glicksman, and the many others who have assisted me.

Section 7 – References

"About MITEI." MIT Energy Initiative website. <http://web.mit.edu/mitei/about/index.html>.

AeroVironment, Inc.: Innovation at Work. <http://www.avinc.com/>.

AWS TrueWind, LLC. *The New England Wind Map.* 2003. <http://truewind.teamcamelot.com/ne/>.

Bates, Richard. "Optimal Rooftop Turbine Placement: On-Site Testing."

Bates, Richard. "Post Report Analysis."

Bates, Richard, Samantha Fox, Katherine McCusker, Kathryn Pesce. "Wind Study: Feasibility Study and Recommendations for Implementing Wind Power on MIT's Campus." May 16, 2007.

Google Maps. <http://maps.google.com>.

"Introduction to Finite Element Analysis." How to Build a Robot Tutorial - Society of Robots. <http://www.societyofrobots.com/mechanics_FEA.shtml>.

"Maps and Floorplans." <https://floorplans.mit.edu/>.

Mertens, Sander and Kuik, Gijs van and Bussel, Gerard van. "Performance of a High Tip Speed Ration H-Darrieus in the Skewed Flow on a Roof." American Institute of Aeronautics and Astronautics Journal 23 05 2003 1-10. <http://www.windenergy.citg.tudelft.nl/content/research/pdfs/aiaa2003-sm.pdf>.

"MIT Campus Energy Use." <http://web.mit.edu/mit_energy/programs/campusenergy/energymap/#>.

"PHOENICS Overview." <http://www.cham.co.uk/phoenics/d_polis/d_docs/tr001/tr001.htm>.

World Consumption of Primary Energy by Energy Type and Selected Country Groups. 1980-2004 (XLS). Energy Information Administration, U.S. Department of Energy.