MODIFYING HABITS TOWARDS SUSTAINABILITY:

A STUDY OF REVOLVING DOOR USAGE ON THE MIT CAMPUS

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PLANNING FOR SUSTAINABLE DEVELOPMENT
B.A. CULLUM, OLIVIA LEE, SITTHA SUKKASI, DAN WESOLOWSKI

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1. INTRODUCTION

This report focuses on a study of revolving door usage on the Massachusetts Institute of Technology campus, which our group completed for the MIT class "11.366: Planning for Sustainable Development."

We chose this obvious yet eclectic topic about revolving door usage due to the themes of the class and due to our personal curiosities about revolving door usage on campus. We were posed with an intriguing question during the initial class session: Can local changes make a big impact? We were encouraged to think of ways in which small changes on a local scale could contribute to sustainable development and eventually help make a global impact. We learned of two methods that could be used to enact change from discussions led by our guest speakers. Change could be initiated by grassroots efforts or by targeting the head decision-makers. We decided to pursue the first of these two options through the study, and set out to find a means of implementing change from the bottom-up.

We also pursued this topic because of several personal observations made on campus that sparked our curiosities. Firstly, people seemed to ignore existing signs asking people to use the revolving doors. People simply preferred using swing doors over revolving doors. Further, the revolving doors, which supposedly conserved energy for the university, were all locked after 6:00 pm on weekdays and all day on weekends. Our observations, combined with our understanding of the class theme, made the study appropriate for the class and motivated us to initiate an examination of revolving door usage on campus.

2. A BRIEF HISTORY: REVOLVING DOORS

It is appropriate to first answer some basic questions about revolving doors before explaining the methodology, experiment, and results of the study. For example, when was the revolving door invented? What was the original purpose of the revolving door?

An American patent was granted to Theophilus Van Kannel of Philadelphia in 1888 for a three-partition revolving door, which he called a "Storm-Door Structure."[1] The door consisted of "three radiating and equidistant wings," with weather strips to "ensure a snug fit."[2] The door was designed to be noiseless, with "numerous advantages over a hinged-door structure" because it prevented the "entrance of wind, snow, rain, or dust."[3] Further, since a revolving door moved only in one direction, streams of people could pass through a building with "reduced possibility of collision."[4]

Today, the revolving door is set on a rotating shaft and revolves in a frame with unlimited rotation.[5] In contrast, regular swing doors are attached to a hinge and only open a maximum of 180 degrees.[6] Most revolving doors have four transparent doors, with pushbars attached to the doors.[7] Curved walls surround the circumference of the

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1 "Revolving door." Wikipedia, The Free Encyclopedia. 15 May 2006. Wikimedia Foundations, Inc. 18 May 2006 <http://en.wikipedia.org/wiki/Revolving_door >.
2 "Revolving door."
3 "Revolving door."
4 Beardmore, Alan. The Revolving Door Since 1881. Edam: Boon Edam B.V., 2000. pg. 9.
5 "Revolving door."
6 "Revolving door."
7 "Revolving door."

revolving door, with an opening that equals the size of one section of the revolving door.[8] This configuration keeps the revolving door closed at all times, and ideally prevents wind from going into the building through the door, thereby helping to minimize the energy needed to heat and cool the building.[9]

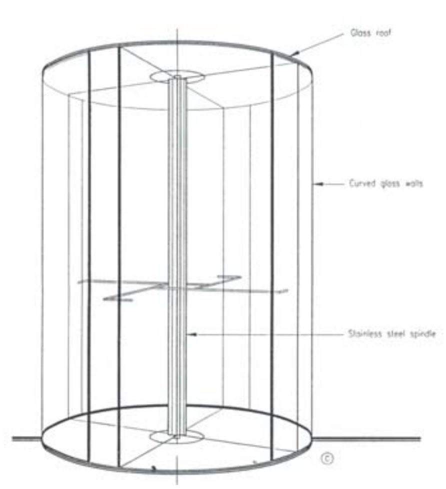

Figure 1.

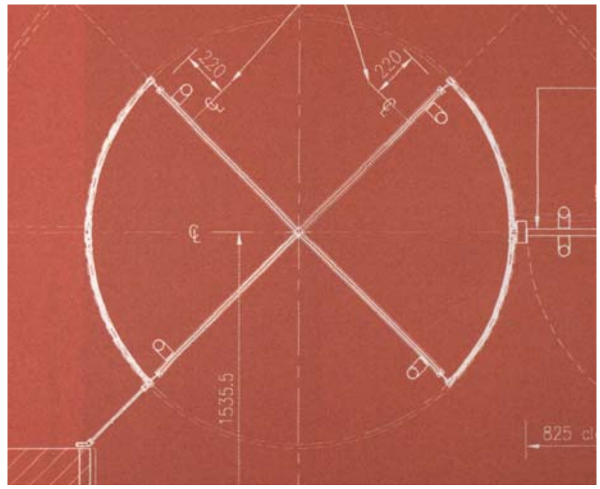

Figure 2.

Figure 1 and 2: Two diagrams depicting a typical revolving door used today. Note the four doors, curved walls with two openings, and pushbars shown on both diagrams. [10]

3. THE REVOLVING DOOR STORY

The revolving door study performed on the MIT campus can be viewed as a story of habit formations (the use of the swing door over the revolving door) and how to modify them (how to get people to use the revolving doors).

Three key questions arise when studying habits:

1) Can habits be reversed?
2) What effectively changes habits?
3) Can having people change one habit have a large impact on the environment?

The study was not initiated to force unwilling people to use revolving doors – therefore, blocking the swing doors was never a goal or option for the project. Rather, the study attempted to influence their almost unconscious door use decisions; it sought to alter their habits. The study also attempted to address the frozen viewpoints of people who may have used swing doors simply because they've "always done it that way."

Door use is a very small part of the overall energy problem, but understanding the experiment as one about habits allows its core message to be expanded to any number of issues. The study addresses each of the three significant questions above, and further illuminates how the idea of implementing change by increasing revolving door usage on campus boils down into a story of habit formations and how to modify them.

[8] "Revolving door."
[9] "Revolving door."
[10] Beardmore 492, 298.

4. PROBLEM STATEMENT

The purpose of this study was to examine people's behavior with regard to revolving door use on campus. Two areas were addressed: habit formation and the identification of effective methods to modify habits. In summary:

> Why is the existing signage asking people to use revolving doors ineffective, and what is an effective means of getting people to use the revolving door over the swing door?

5. PRE-EXPERIMENTAL DESIGN: SURVEY

A survey was conducted before designing and conducting the door use experiment in order to build on the initial observation that people used swing doors over revolving doors. The survey provided a means to check if the preliminary observation was true. Further, the survey allowed for insight to be gained into why people chose the options they did when presented with both types of doors at an entry/exit point. The survey also checked if people had a threshold number of energy that would have to be saved from using the revolving door for people to switch over. Lastly, the survey helped pinpoint different factors that would influence people to begin using revolving doors over swing doors.

The following four questions were asked to a group of thirty-three undergraduate students:

1) When both a revolving door and swing door are available at an entry/exit, which do you use most often? *[Revolving door or Swing door]*
2) Why do you use this type of door?
3) How much more energy would have to be saved by using revolving doors over swing doors for you to feel that using revolving doors is worthwhile?
   [5%, 25%, 50%, 75%, 100%, Other, or "I already use revolving doors regularly"]
4) Which of the below influences you to use revolving doors?
   [Signage hung on doors about energy savings, Person ahead of you used the revolving door, Your personal knowledge about energy saved from revolving doors, Other]

Sixty-four percent of students responded that they used the swing door over the revolving door, verifying initial observations about door use. Observations performed in this study show that the swing door usage percentage is actually much higher.

Students were asked an open-ended question about why one chose either the swing door or the revolving door. The students made comments that often fell into one of a few common categories.

Of the swing door users (the majority – 64% of those surveyed), one student said, "The swing door is easier to use," while another noted, "The swing door is quicker, and requires less effort." Another user noted, "The revolving doors on campus are not well maintained and usually hard to push." Yet another student expressed a number of frustrations in the survey: "I use the swing door because it feels faster to me. Some people push revolving doors slowly or get clogged in them. Sometimes the guy behind you pushes fast because he's in such a hurry, and this causes you to get slammed with the door. At other times, some lady with too many packages gets stuck, and you're then stuck until she figures her life out. The revolving doors are stressful." These comments, and those of other swing door users, made it clear that the majority used the swing door for one or more of the following reasons:

1) The revolving doors are stressful.
2) The swing doors are quicker.
3) The swing doors require less effort.
4) The revolving doors are dangerous, cramped, and I am fearful of getting stuck in them.

A minority of students already used the revolving door. One revolving door user commented, "I will always user the revolving door if it is not locked. I do this because I think it wastes less of MIT's heating and cooling power." Another revolving door user noted, "I use the revolving door because it saves energy! I hate how swing doors at MIT say 'Please use the revolving door to help MIT conserve energy' and no one does! Plus, revolving doors are more fun." From the comments, it is clear that altogether, the revolving door users (the clear minority of students) did so for one to two of the following reasons:

1) The revolving door is energy efficient.
2) The revolving door is fun and entertaining.

For those students who regularly used swing doors, the majority felt they would switch over to using revolving doors if 50% more energy was saved by using revolving doors over swing doors. Only one student said she/he would never use the revolving door.

When asked what might prompt one to choose the revolving door over the swing door, 42% of students said signage hung on doors about energy savings would influence them, and 61% noted that they would use the revolving door if the person ahead of them used the revolving door. Thirty percent of students also noted that personal knowledge about energy savings would influence them to choose the revolving door. Each student was allowed to circle more than one option.

The survey clarified several points. Firstly, the majority of student surveyed did use swing doors over revolving doors. Of those who used revolving doors, many did so because they were personally knowledgeable about the energy savings that accumulate from using revolving doors. Most importantly, of those who used swing doors, the survey revealed that the majority were not extremists – that is, they were not people that were adamantly against using the revolving door at all times in any situation. This information made it even more appropriate to initiate a study that attempted to modify the habits of people who used the swing door. Lastly, many of the comments were helpful in designing the experimental process. Some comments noted that people did not use the revolving door due to the force needed to push them. Testing for issues like the force needed to push doors were factored into our methodology, and the study was able to lend concrete data to validate or invalidate the comments.

6. POSSIBLE APPROACHES TO CHANGE HABITS

A number of approaches to change peoples' habits regarding revolving door use were considered following the completion of the survey. Choosing an experiment that could prompt individuals to use revolving doors was key. However, the selection of a single approach to address the problem proved to be a challenge due to the wide range of options under consideration. The options were classified into three distinct approaches to clarify the different experimental paths that could be taken.

The first of these approaches, Physical Design Modification, intended to change individuals' revolving door habits by adjusting certain physical features of building entryways that contained both revolving doors and swing doors. Modification of building entrances could take the following forms:

- *Installation of new revolving doors that would have prominent locations at building entrances.* This type of construction has occurred on the MIT campus at Building E51 (Tang Center).
- *Placement of revolving doors closer to flows of pedestrian traffic than swing doors.* The revolving door would serve as the first opportunity for entry into a building.
- *Automation of the revolving doors.* This option would address the concern that too much force was required to push through revolving doors.
- *Locking of the swing doors adjacent to revolving doors.* In this instance, locks would not allow people to enter buildings through swing doors, forcing them to use the revolving doors. Building code requires that the locking mechanisms allow people to exit the swing doors.
- *Placement of swing doors at harder-to-find locations at building entrances.* By making it more difficult for people to locate swing doors, they will opt for the revolving doors.
- *Increase the force required to open swing doors.* Making it more strenuous to open swing doors will encourage people to select the easier-to-push-through revolving doors.

Figure 3.

Figure 4.

Figure 3: An example of the first modification above - the entrance to Building E51 (Tang Center) has a new revolving door with a prominent location. Figure 4: An example of the fifth modification above - the swing door on Building 54 is hidden behind this revolving door.

The second of the three approaches, Active Involvement, involved direct interaction with people whose door usage behavior was targeted for change. While the first approach focused on affecting individuals' decisions through physical changes to building entrances, this second approach provided opportunities for the education of door users about the consequences of their decisions. Directly encouraging revolving door use included the following options:

- *Position a revolving doorman who could push people through next to a revolving door.* Similar to the automation of a revolving door, this option also addresses the complaint that too much force was required to use revolving doors.
- *Position a revolving door monitor next to a revolving door.* People would recognize that this monitor, clipboard in hand, was watching their choice of door, and the monitor's presence would persuade them to use the revolving door.
- *Establish a pledge drive.* A pledge drive, announced in office buildings, campus dorms and elsewhere, would get people to pledge (sign their signature) that they would use revolving doors. Such a pledge would give them greater awareness of their door usage actions.
- *Launch a building competition.* This competition would pit workers in different office buildings or students in different dorms against each other to determine which building's occupants could achieve the highest level of revolving door use.
- *Have activists distribute flyers.* Passing out flyers captures people's attention and offers the opportunity for conversation between activists and door users about the benefits of revolving door usage.

The third and final approach to changing people's revolving door use habits, the Marketing Approach, promoted the use of revolving doors through signage. This approach is currently employed by MIT. The majority of building managers who are faced with the task of optimizing building energy use do not have the option to demand a change to the building entrances, making the Physical Design Modification approach impractical. Additionally, these building managers also probably lack the resources to carry out alternatives suggested by the Active Involvement approach. A less drastic and less expensive means for encouraging revolving door use is necessary. Signage proved to be the best option.

The current signage used by MIT, however, has been ineffective. At Buildings 66 and E25, for example, double-sided signage stickers have been placed on the swing doors to encourage use of the revolving door, but these signs are blatantly ignored. This disregard is evidenced by the 8% revolving door use at Building 66 and 23% use at E25. Several possible reasons point to why the signs are ineffective – they are small in size, they are damaged, and they have been posted on the doors for a long period of time. Each of these reasons would contribute to the diminished impact of any message displayed on these signs.

Figure 5. The small, worn signage at E25.

Though MIT's existing use of signs is unsatisfactory, the approach of using signage to change habits is still valid – it is possible to stand on the shoulders of MIT's attempts and improve upon those attempts. A different approach to using signage, involving redesigned signs, could include the following options:

- *Replacement of existing signs with new signage.* Although still small, new signage could catch the eyes of door users and impact their actions.
- *Installation of larger signs.* New, larger signage would have greater visibility from afar and enhance the possibility of affecting people's habits.
- *Placement of new signage on stands in front of building entrances.* This option would draw attention to the signage by separating it from the building entrance.
- *Adjustment of the message on the sign.* Changing the message on signage could more effectively communicate information to door users.

The Marketing Approach was selected after consideration of these three approaches. The decision was based on several factors. Only the MIT Department of Facilities had the ability to modify building entrances, and working with the Facilities Department to implement physical changes to entryways would have been a difficult, time-consuming, and potentially costly process. Additionally, a lack of resources such as manpower and money made direct interaction with door users a challenging task. The Marketing Approach was seen as an efficient method through which an impact on revolving door usage could be achieved.

7. THE DOOR USE STUDY: A MARKETING APPROACH

The Marketing Approach can be seen as a method of persuasion. The purpose here, of course, is to convince as many people as possible to use revolving doors instead of swing doors. With this idea in mind, an important step in the experiment would be to redesign MIT's signage so that it more effectively communicated the desired action of revolving door use to potential users.

Two individuals were consulted to help address the issue of signage design. Firstly, advice was sought from Dr. Sharmila Chatterjee, a visiting Professor of Marketing at MIT's Sloan School of Management. She provided several insights about how to best to bring a message to the attention of pedestrians moving through door entrances:

- Catchphrases and graphics should be the key elements considered in the design. Pedestrians scanning over signage will first look at these two features.
- Use one to two main catchphrases to communicate the preferred intent.
- Use large lettering to ensure that pedestrians could read catchphrases clearly and from a distance.
- Avoid an information overload. The presence of too many elements on signage would dull the message.

Advice from a second source was also integrated into the signage design. A discussion with Laxmi Rao, the Information and Technology Project Manager in MIT's Department of Information Services and Technology, prompted the inclusion of the following ideas:

- Branding should be an important element in signage design. The potency of the new signage would be enhanced if people could immediately recognize it as a symbol of energy conservation.
- For branding purposes, an image should be placed on the signage alongside the signage. This image would reinforce the identity of the sign.
- The image should be used consistently on all signage. Such consistency would help people associate the signs with energy conservation even if the catchphrases on the signage were to vary over time.

These recommendations would be factored into the signage design, but before the design process could be initiated, the character of the signage also had to be considered. Determining the character of the signage involved a decision over what kind of reaction the signage should attempt to generate. Should the sign be framed as a kind request asking individuals use the revolving door? Should it attempt to educate individuals on revolving door use in order to convince them why their actions were important? Should it include humorous content as a means to make the energy conservation message endearing to door users? Should it scold swing door users about their decisions in order to cause feelings of remorse? It was determined that the kind request, favored for its straightforward approach, would be used in the primary signage design. Additionally, the information-based educational approach would serve as the basis for a secondary signage design. Based on these decisions and the guidance of both Dr. Chatterjee and Ms. Rao, the following signs were created:

Figure 6. The primary sign design directly asks individuals to use the revolving door.

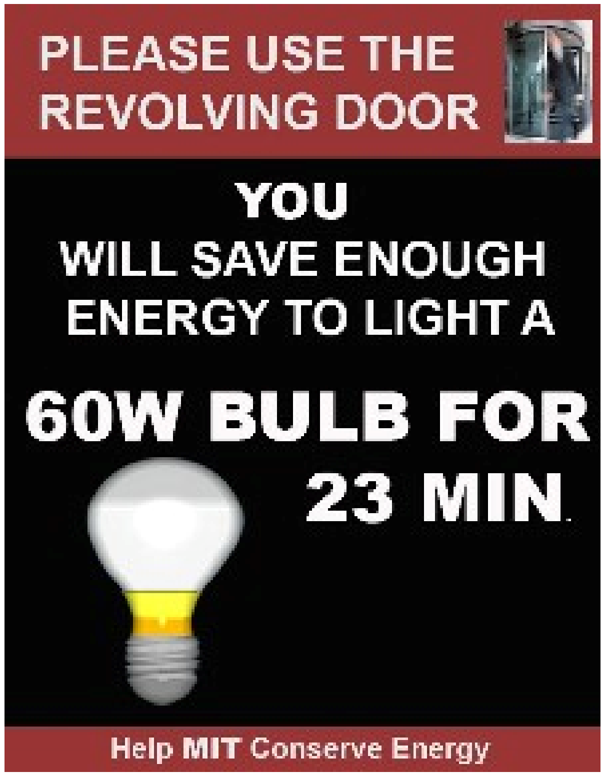

Figure 7. The secondary sign design provides information to individuals.

The recommendations provided were incorporated into both of these designs, as demonstrated by the use of central catchphrases, large lettering and the consistent placement of the revolving door graphic in the upper right section for branding purposes. The primary sign was to be used for the majority of the door use study, while the secondary design would be implemented in certain instances. After developing the Marketing Approach, the complete methodology for the door use study was created.

8. METHODOLOGY

The door use study was to account for the existing revolving door usage as well as the impact of different signage experiments on people's behavior in order to evaluate the effectiveness of the Marketing Approach. Therefore, to address these issues, two separate studies were completed.

The first study focused on breadth and involved monitoring current revolving door use across the MIT campus. The buildings tested included the entrances of MIT buildings 9, 34, 39, 46 (Brain and Cognitive Sciences), 54 (Green), 66, E15 (Wiesner Building – Media Lab; both 1st floor doors), E51 (Tang Center), NE48 (600 Tech Square), and NE49 (700 Tech Square).

The second study focused on depth and involved the implementation of different signage options associated with the Marketing Approach on one building. E25 (Whitaker College) was selected as the site on which to conduct the experiments. The building was chosen due to its high level of pedestrian traffic on weekdays, which occurs due to its proximity to the Kendall/MIT MBTA station, and due to the route it provides into the inner MIT campus, particularly its access to the Infinite Corridor.

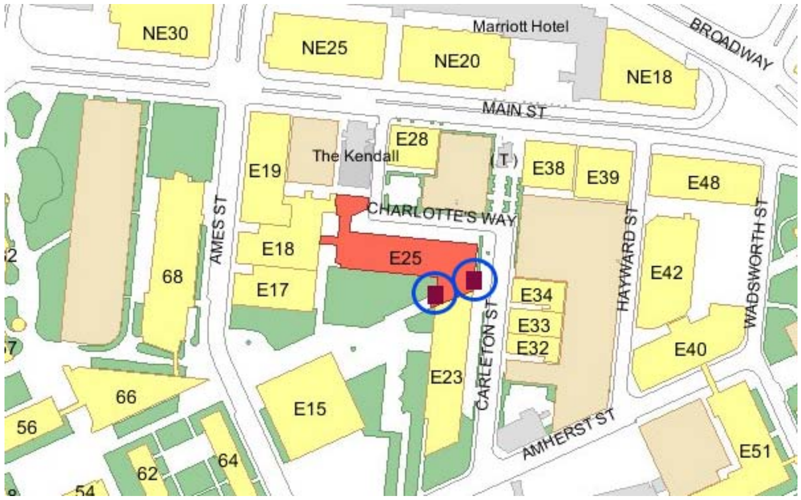

Figure 8. Building E25's entrances, with revolving doors and swing doors on each side.

Sign size was altered to determine whether making the signage more obvious to door users would improve the rate of revolving door use. Several different sizes were selected to determine if signage dimensions needed to reach a certain threshold for the message to have effect. Door use was monitored at E25 using signage of the following measurements:

- Control (existing worn 4.5 inches x 5.5 inches MIT signs)
- 4.5 inches x 5.5 inches
- 8.5 inches x 11 inches
- 11 inches x 17 inches

Additionally, signage was placed in three different positions at both entrances. Similar to the modifications of signage size, these positions were selected to find out if more noticeable signage (due to the change in positions) would improve revolving door usage, or if this approach would remain as ineffective as MIT's current approach. Signs were set up at the following positions:

- On the swing doors located on both sides of the revolving door.
- On stands in front of the swing doors, with one stand per side.
- On stands to the right side (when facing the entrances) of swing doors, with one stand per side.

This second study was performed on consecutive days, with a different signage size used on each day. Signs were made progressively more obvious each day. The control situation (no new signage) was tested both before the new signage testing and two days following the testing of the largest, most obvious signage. The data indicates no significant change in this revolving door use rate from the pre-implementation control to the post-implementation control, indicating the results from each day are independent of each other. Furthermore, new signage was only posted facing the outside of the building, and the revolving door use rate was monitored only for users entering the building. Since almost all users of the E25 doors pass straight through the building, a difference in revolving door usage during the signage implementation period should provide some indication of how much of an impression different signs made on the users. The experiment results section below explains the details of these impacts, as well as the overall results of both parts of the door use study experiment.

9. DOOR USE STUDY: RESULTS

The door use behavior study results were extracted from 47 combined hours of observations made at eleven different door locations, some with multiple revolving doors. This significant effort resulted in many qualitative observations that provided insight into why users select particular doors. These observations strongly suggest door use habits, rather than conscious decisions, usually control door selection. Furthermore, these habits are not fixed, but can be modified through simple, marketing-based approaches. Quantitative analyses of door use at a number of locations around campus were used to substantiate this claim. The studies performed indicated effective ways to modify user habits to substantially increase revolving door use.

9.1. OBSERVATIONS

A number of qualitative observations imply user habits have the central role in door selection. Habits form because they represent the easiest method for an individual to accomplish a task subject to constraints. The formation of habits occurs with repetition of a behavior resulting in a reward.[11] Door selection habits result from experience in selecting the door that requires the least energy to open. The highest revolving door use rates were found in buildings with constraints on the swing door use. Figure 9 below shows examples where the swing door is hidden behind the revolving door by extending the revolver out of the building with a duct and placing the swing doors in this duct. The example buildings have revolver use rates of 77±7% (Bldg 54) and 84±19% (E15). This compares to a control (unconstrained doors) average of 23±2%. Recall, the self-reported revolving door use rate was 33%.

Figure 9. Revolving doors with hidden swing doors. Building 54 (left) and E15(2) (right) have revolving door use rates of over 75%. Swing doors are hidden from approaching users.

[11] Windholz, George. "Protopopov's ideas on habit formation and their relation to the Pavlovian theory of higher nervous activity." American Journal of Psychology. 112.3 (1999): 437-448.

Other observations also indicate the easiest door to use is most often chosen. E25 connects the main campus to the subway station, and most users walk through the building. However, the design of the building places the left swing door is closest to the station. Almost 60% of users here pass through the left swing door; the remainder split roughly evenly between the other two doors. Survey results show that people avoid the revolving doors because they are hard to push. Several individuals were observed testing the revolving door gently, then moving to a swing door. On the other hand, 80% of individuals who found a locked swing door chose to go through the next closest door - the revolver. Persons who appear to be in a hurry often chose swing doors rather than the revolver. Workers (office workers or contractors) in mixed office/commercial spaces (NE49, NE48) often pulled the swing door to come in, while customers tended accepted the more leisurely pace of the revolving door. A strong preference to push doors was observed. Twenty-one of the twenty-four users of the right swing door at NE48 pushed the door and went out; almost all had previously pushed on the revolving door to come in. Less energy is required to push a door than to pull it because the momentum of the person contributes to opening the door.

It would seem to follow that revolving doors that are easy to push are more likely to be used. The force to start revolving doors was tested at the locations examined. The results, shown in Figure 10 below, do not seem to substantiate this claim; no correlation between revolver use and force was found. However, the energy required to open a door is a product of force and distance, and revolving doors require the application of force over about twice the distance of a swing door. Therefore, swing doors actually have to require more force to open than revolvers for an equal amount of work to be dissipated in opening the doors.

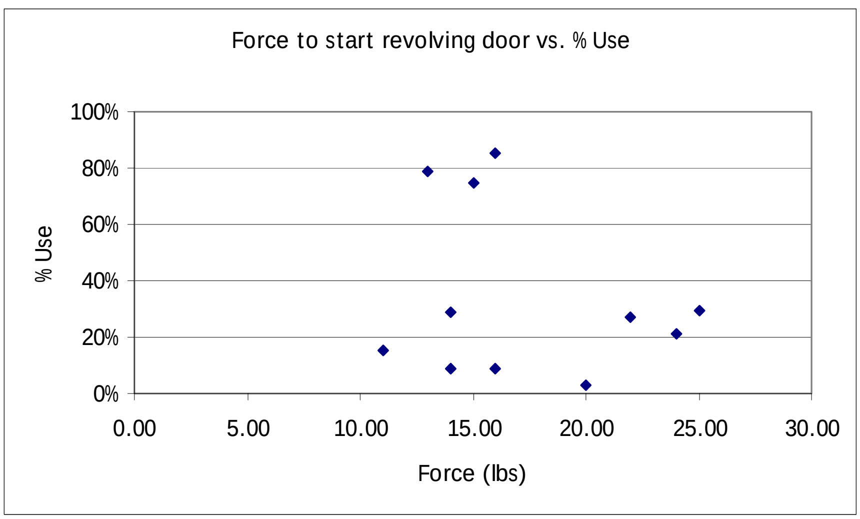

Figure 10. Force to start revolving door vs. % [percent] revolver use. No correlation is observed, but the starting force for all doors considered might be too high. The three outliers are 54, E15 (2), and NE49, which have other reasons for high revolving door use rates.

A numerical example highlights the problem. The swing doors tested require about ~12lbs of force to open. The control revolvers at E25 required 23lbs of force over about ¼ the distance of swing to start, and 11lbs to sustain the motion of the revolving door. The swing radii of the revolving door and swing door are the same (L). The average swing door therefore requires 12L ft-lbs of work to open. The revolver requires (23 L/4 + 11 3L/4) = 14L ft-lbs of work to open. Moreover, a user gently testing the revolver doesn't know the force will drop after the revolver starts, so it seems as though it will require almost twice the energy to open the revolver as the swing door. The large change in the user's momentum may promote revolving door use in, but users have a large personal energy incentive to push the swing door out rather than deal with the revolving door.

The easiest door to use is the one that is already open. The previous user selecting a door is an overwhelmingly powerful driving force for following users to choose that door. This probably has as much to do with custom as work - it seems impolite to refuse a door held open, for instance. However, even if the swing door is not held open, users will run up to a closing door and try to "catch" it. This becomes problematic at locations with high traffic. The swing door closest to the subway station at E25, for instance, was often open the entire time it takes for a trainload of people to pass through the doors. Another example was the observation of two people who waited for an entire shuttle bus of people to pass through a swing door before going out the same door, rather than opening either the unused swing door or using the revolver.

The desire to follow through open doors sometimes actually encourages revolving door use. Many people waited to go through the revolving door if the swing door was not open and the revolving door was moving (usually because the first person in a group had chosen the revolver). This minimizes work because the first user has to overcome the inertia of the door, and two users pushing on the door halve the force required to turn it. High traffic rates discouraged this behavior - eventually a user was unwilling to wait and opened the swing door, with other users following this initial user through.

Users are surprisingly adept at minimizing energy expenditure while passing through doors. Perhaps using the open door or the closest door is an obvious decision, but choosing to push a revolving door in and a swing door out is not. Very likely none of the users who walked through the doors consciously decided to follow the work minimizing path - they simply followed their habits. Minimizing work while going through doors drives the formation of these door selection habits. Building managers interested in saving money and conserving energy must find ways to modify these habits to minimize total air infiltration through the doors.

9.2. QUANTITATIVE ASSESSMENT OF HABIT MODIFICATION METHODS

A number of techniques for modifying door selection behavior were considered for examination. These alternatives were discussed at length in the "Possible Approaches to Change Habits" section above. The options selected for study fall into two general categories: door design and marketing / signage. Figure 12 below illustrates the results of a building-by-building comparison of revolving door use. The results of the door count comparisons were used to compare design features. Figure 13 below shows the results for various signages placed on the doors at E25. Ninety-five percent confidence intervals for the mean are overlaid on each point.

Control studies for revolving door use were performed at both doors of E25. The door closer to the subway was labeled E25(1) and the door across the building, facing the main campus, was labeled E25(2). These doors have the highest traffic rates on campus (837 people/hr average), providing the largest sample for our observations. Revolving door and total usage rates over 5 minute intervals between 9AM and 6PM for these doors were used to determine baseline rates. The doors have the standard, three-door configuration with the revolving door in the center (Figure 11). The plane of the revolver is in the plane of the building.

Figure 11. E25(2) doors. This is an example of the standard configuration for a revolving doors set.

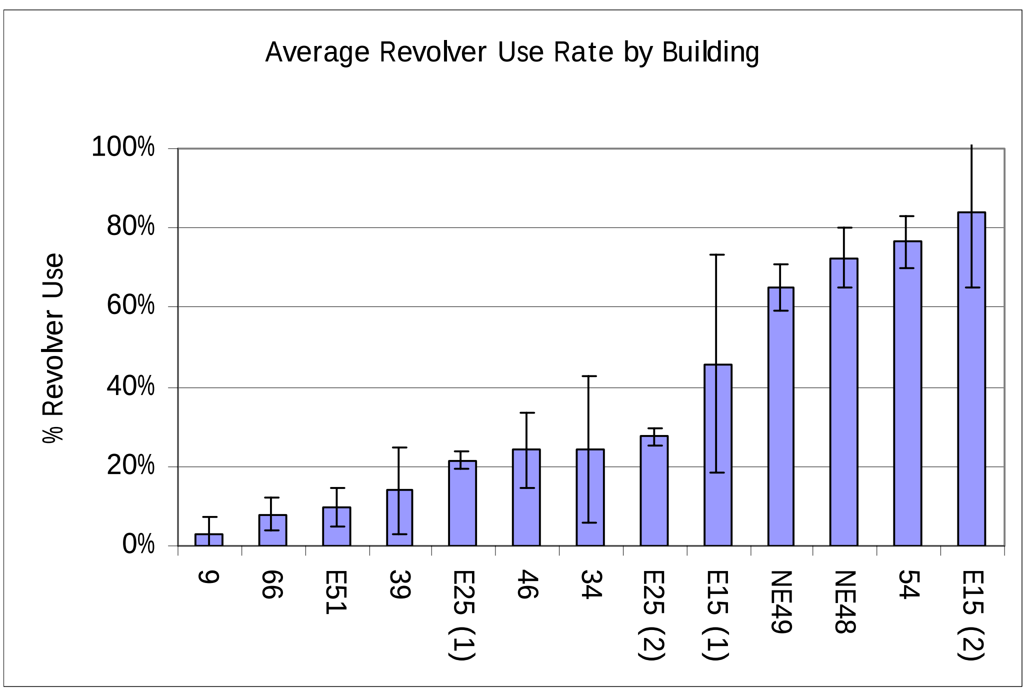

Figure 12. Average revolver use rate by building. Two populations of data are seen. High revolving door use rates are found in buildings with constrained swing door use or effective signage.

Very large discrepancies in door use were observed. Buildings NE48 and NE49, Tech Square buildings, are not owned by the university and require special consideration. Most of the variation in use on campus is directly attributable to design, but not all design modifications are effective. Effective designs for encouraging revolver use include buildings 54 and E15(2), which have revolving door use rates 3-4 times higher than other doors on campus. Both of these doors have hidden swing doors and revolving doors placed forward of the building (Figure 9 above). Placing the door forward of the building alone is not enough; buildings E51 and 66 have this design but these buildings have the swing doors on either side of the revolver and they are easily seen. Traffic through the revolvers in these buildings was actually well below the control average of 23% taken at both doors of E25. Another possible way to encourage revolver use is to put in new or stylish doors. Buildings E51 and 46 have new revolving doors, and the doors at E51 have a unique design to accent the façade of the building. Revolving door use was no higher than the control in either case. (Please refer to Appendix A for images of all the revolving doors studied.)

The two doors at E15 provide an interesting comparison of the revolving door use for the same sample of users. E15(1) has the same doors and configuration as the control doors, while E15(2) has a hidden swing door design. Both doors open to the same ground floor lobby. The use rate at E15(1) is significantly (p = 0.03, two-tailed t-test) higher than other similarly designed doors with similar traffic rates (9 and 39). The data suggests users of that building are in the habit of using the revolving door - 85% use it when going through the unique door, and, being accustomed to using it, they choose it more often when faced with a less obvious choice.

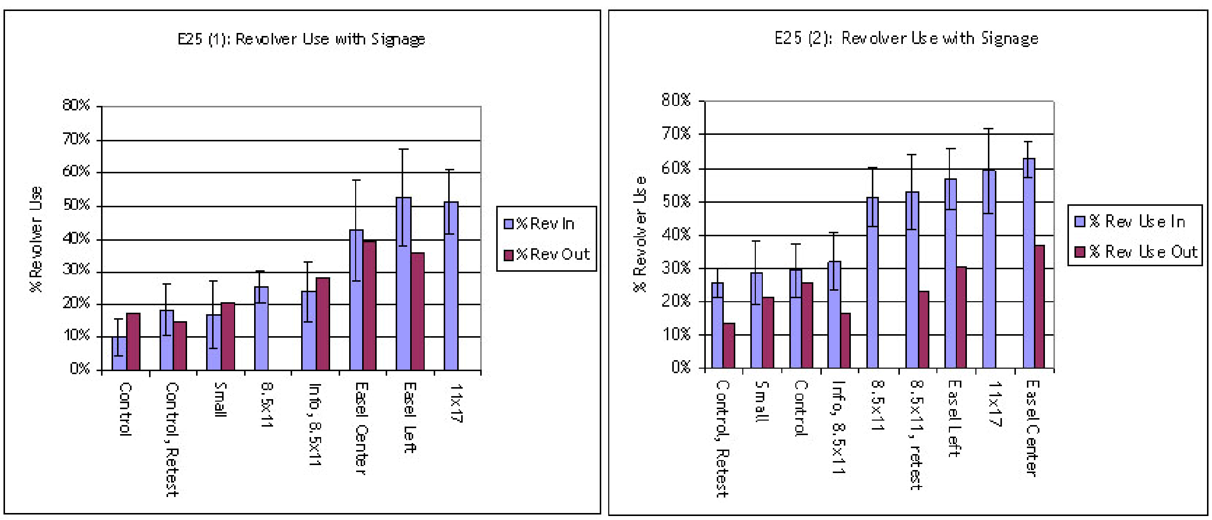

Figure 13. Results of signage study. Revolving door use rates approach that of constrained door designs when appropriate signage is installed.

A series of experiments were performed at E25 between 4:50 and 5:50 PM (the evening rush hour) to see what signage could encourage revolver use. The results are shown in Figure 13. Revolving door use was universally higher for E25(2) than for E25(1). This is due to the left swing door of E25(1) being close to the subway station. The control revolving door use rates for either door is not significantly different than 23%, except for the first control test at E25(1), which was slightly lower.

The effect of signage size was checked first. The implementation of new signage the same size as the original signage had no effect; the mean revolving door use rates were almost exactly the same as control. This indicates that "banner blindness"[12] was not responsible for the low revolving door rates; even new signs had no effect. The implementation of 8.5"x11" signage of the same message yielded mixed results. Users approaching from campus to E25(2) have a longer time to look at the doors and the smaller signage may have influenced them more than users approaching E25(1) from the subway. The largest signage (11"x17") worked well when placed on either door, increasing revolving door use by at least 200%. The 11"x17" signs worked equally well or even better when placed on easels in front of the doors, regardless of their positions with respect to the doors (off to the left or centered).

The effect of the message on revolving door use was examined next. New 8.5"x11" signs (as shown in Figure 7 above) with an information-based message telling people how much energy they could save by using the revolving doors were made. It was hypothesized that people would see the sign and would want to help the community by saving energy. This was not the case. The sign had no effect on use at E25(1); this is perhaps understandable given the wordiness of the sign and the short time people have to read it. People approaching E25(2), on the other hand, actually ignored the information-based sign. Roughly 40% fewer people chose the revolving door with the information-based sign than with the "kind request" sign of the same size. Several pairs of people were observed walking through the swing doors, pointing at the signs and discussing them. Clearly, the sign sparked interest in the problem, but it did not change behavior.

The difference between revolving door use in and out of the building is complex. The preference to push swing doors is clearly seen in the drop in revolving door use for E25(2) for all signs. The drop in revolving door use is lower going out E25(1). This may be because users that approach E25(2) see signage for a longer time and may be more likely to remember it when they exit E25(1) across the building (usually about 30 seconds later). Still, the residence time for the signage is overall pretty low. For example, E25(2) revolver use was 63% for 11"x17" signs on center placed easels. The revolving door use rate out was only 39%; 40% of revolving door users decided to push out the swing door rather than use the revolver again.

9.3. EFFECTIVE SIGNAGE AND HABIT FORMATION

The results of the signage study suggest that engaging people at the level of habit is important for modifying door use behavior. Signage is effective only if it is large enough for users to notice at a distance. The longer that distance, the more effective it is. Users approaching a door are not consciously thinking about which door to choose, but instead are subconsciously processing cues to determine - with great acuity - which door will be easiest to go through. Getting users to think about their door choice is not the answer. Few users really want to push through the revolving door. Sixty-four percent of users in the survey responded negatively towards revolving doors when they are asked about them. Telling users this is a choice that helps save energy / the environment makes the door selection seem burdensome - and few actively choose it. Large signage with a simple message, such as "Go through the revolving door!" guides users towards the door without making the user wonder why. One door user noted he found himself walking towards the revolving door when there was simply an arrow on the swing door pointing to the revolver, even though the sign was unrelated to revolving door use.

[12] A stimulus loses its effectiveness with repeated application; this is called habituation. A good example is "banner blindness: how Internet users quickly learn to ignore banners on websites." See Benway, J. P. (1998). "Banner blindness: The irony of attention grabbing on the World Wide Web." Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting. 1: 463-467.

Habit formation is not instantaneous, but once formed it is difficult to break. The high revolving door use numbers at NE48 and NE49 demonstrate the efficacy of extended signage implementation. The university leases space from these buildings from an outside provider that has been aggressive in pursuing increased revolving door use. The revolving doors are in good condition and well maintained, with a starting force only slightly higher than swing door use, and the doors are placed forward of the building. These factors alone do not lead to high revolving door user rates, as demonstrated by numerous counterexamples around campus. One swing door at NE48 is locked from the outside, which did increase revolving door use somewhat. Six percent of users chose the other swing door after finding the first swing door locked; 80% of those who found the locked swing door used the revolver. The mixed office/ commercial nature of the building increases the number of casual users who are more inclined to use the revolving door.

However, the biggest reason for increased revolving door use at these buildings is signage. 8.5"x11" signs requesting users use the revolving doors to save energy were placed on stands in front of revolving doors for the duration of the winter. The signs had been removed for about a month when the door use was counted. Still, revolving door use rates (65±6% and 75±8%) were comparable to use rates with signage on easels in place at E25(2) (63±5%). Users got into the habit of using the revolving door with the signs in place, and, lacking a strong driving force for resisting that habit, they continued to use the revolving door long after signage had been removed.

9.4. RECOMMENDATIONS FOR DOOR DESIGNS

The door use behavior study has a number of implications for door design to minimize heat loss through the building. Following these suggestions can have dramatic impacts on energy consumption. Many of these recommendations have attractive payback times, as will be discussed in the next section.

- Revolving doors must be approximately as easy to push as swing doors. Tighter seals around the door do not reduce air penetration through the door and instead deter use of the door, which increases air exchange dramatically more than leaky weather stripping.
- Door maintenance is important. Door use selection is tied closely to the minimum exertion path. Users will continue to choose the revolver long after the signs are removed if it is easy to use. That said, new or stylish revolving doors alone will not increase use.
- Large signage with a simple message such as "Please use the revolving door" roughly doubles the number of people that use the revolving door. The sign must be noticeable from a distance - far enough away that users can react to the sign before they have made a decision about which door they are going to use. Smaller signs on easels in front of the door are also effective.
- Place revolving doors in moderate traffic areas (100-300 people/hr). Traffic rates that are too low do not adequately take advantage of "following" and new users are likely to pick the swing door based on previous bad experiences. Revolving doors are not fast enough for very high traffic rates, and users will just open the swing doors. A vestibule double-door design is a better partial air-lock alternative.
- Locate the revolving door closest to where the majority of traffic is coming, or better yet, hide the swing doors behind the revolver. Lock the swing door for entrance if possible.

10. DISCUSSION: INTERPRETATION OF RESULTS

The door usage rates as shown in the above results section can be interpreted in terms of their implications on the building and the environment, namely:

- Air leakage into and out of the building through the doors
- Energy consumed by the air-conditioning equipment of the building to heat or cool the displaced air
- Cost of the consumed energy
- Carbon dioxide emission associated with the generation of the consumed energy

10.1. AIR LEAKAGE ESTIMATION

Air leakage, both natural ventilation and infiltration, through a door is driven by the pressure difference across the building envelope caused by wind and air density difference, which, in turn, is due to the temperature difference between indoor and outdoor air.[13] Air leakage is most commonly measured and referred to as a *rate*, with a unit such as cubic feet per minute (cfm).

For both revolving and swing doors, air leakage occurs in two ways: through the door's seals and cracks while the door is closed and through the door's passage while the door is opened.[14] [15]

The methods and assumptions used in this study's air leakage estimation are obtained from handbooks and technical papers published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Some results can be obtained analytically with formulae, but others can only be interpolated based on charts produced from experimental results.

Air leakage through revolving doors

Air leakage through a revolving door is a combination of air infiltration past door seals and cracks when the door is stationary and displaced air due to the revolving of the door.

The infiltration through door seals without visible cracks depends on the indoor-outdoor pressure differential and the configuration of the door wings relative to the housing, whether all four or only two wings are in contact with the housing. Similarly, the infiltration through door seals with visible cracks depends on the indoor-outdoor pressure differential and the size of the cracks. (These two types of infiltrations can be estimated by using Figure B1 and B2 in Appendix B).

The air leakage due to the revolving of the door depends on the passage rate, the indoor-outdoor temperature differential, and weakly on the outdoor wind speed. (If the number of users is higher than 250 passages per hour, the infiltration due to the revolving of the door can be directly obtained from Figure B3. Otherwise, the door's

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[13] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2005 ASHRAE Handbook: Fundamentals. Atlanta: ASHRAE, 2005.
[14] Schutrum, L. F., et al. "Air infiltration through revolving doors." ASHRAE Journal 3.11 (1961): 43-50.
[15] Min, T. C. "Winter infiltration through swinging-door entrances in multi-story buildings." Heating, Piping and Air Conditioning 30.2 (1958): 121-128.

average revolving speed, in revolutions per minute, and operating time fraction need to be estimated first, using Figure B4. Then, with the estimated averaged revolving speed, the infiltration can be obtained from Figure B5).

Previous experiments showed that the air leakage due to the revolving of the door is practically independent of the pressure differential and that the leakage past the door's seal does not change significantly when the door revolves.[16] Thus, it is valid to calculate the total air leakage due to revolving door usage by simply summing the leakage past door seals and cracks and the displaced air due to the revolving of the door.

Air leakage through swing doors

Air infiltration due to swing door usage depends on the indoor-outdoor pressure differential and the so-called *entrance coefficient*, which depends on the door passage rate, whether or not the door has a vestibule, and whether or not the obstruction by the users' bodies is significant. (The entrance coefficient can be obtained from Figures B6 and B7. Once the entrance coefficient is known, the infiltration due to the swinging of the door can be estimated by using Figure B8).

Similar to the air leakage through a revolving door, the total air leakage through a swing door is a combination of the infiltration due to the swinging of the door and the leakage past door cracks.

Indoor-outdoor pressure differential

Evidently, the indoor-outdoor pressure differential is an important driver of air leakages through both revolving and swing doors. The total pressure differential is coupled by two components: stack pressure difference and wind pressure.[17] (Equation C1 in Appendix C shows how to calculate the total pressure differential).

Stack pressure is caused by the weight of a column of air. Thus, the indoor-outdoor stack difference is a function of indoor and outdoor air temperatures and densities; the height of the air column, which is commonly taken as the height of the building; and the height of the point of interest, which, in this case, is the height of the door[18] (Equation C2 shows how to calculate the stack pressure difference).

Wind pressure is a result of wind impinging on the building and is a function of the wind direction, building orientation, wind speed, air density, and surrounding conditions[19] (Equation C3 and Figures B9 and B10 can be used to calculate the wind pressure).

Calculation Results

This calculation uses door-usage data obtained from the experiments on building E25, which has an average of 837 passages per hour (23.3% through the revolving doors). The weather data are based on historical records from April 2005 to March 2006. (The complete data is shown in Table D1 of Appendix D). Since the temperature of the

[16] Schutrum, L. F., et al 43-50.
[17] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
[18] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
[19] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

lobby/atrium area is usually not as tightly controlled as the other parts of the building, the indoor temperature for this calculation can be assumed as 72 °F throughout the year.[20]

The swing doors at building E25 have no visible cracks, but these calculations assume total visible cracks (between the door seals and the floor or door housing) 10 inches long and 0.5 inch wide. This makes the current calculations conservative and applicable as the weather stripping deteriorates.

A monthly-averaged total air leakage (for all swing and revolving doors) is calculated for each month. The higher leakages occur during the winter months, as shown in the figure below. The annual average is 2949.7 cfm.

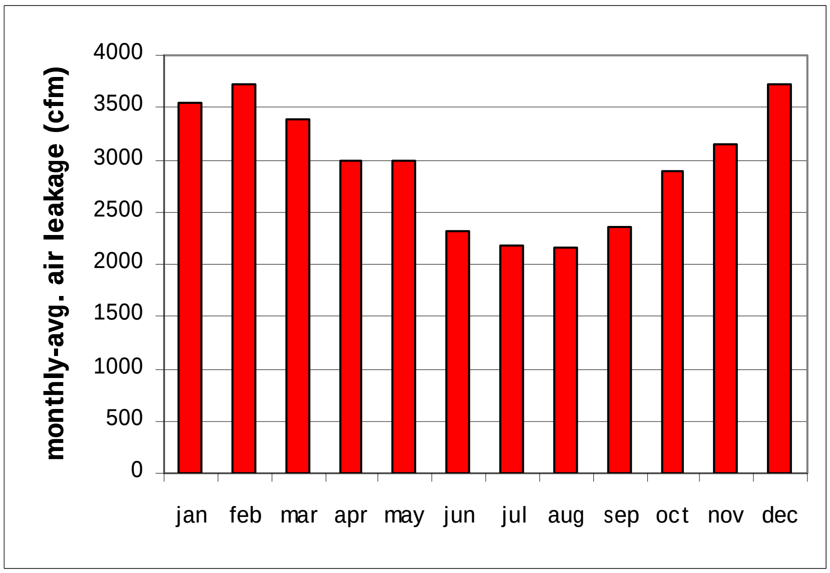

Figure 14. Monthly-averaged total air leakages through building E25's doors (revolving-door usage = 23.3%)

10.2. ENERGY CONSUMPTION AND EMISSION ESTIMATION

The air leakages rate and the operating time of the doors affect the total volume of displaced air within a specific time period. This study assumes that the doors operate 9 hours a day. The volume of the displaced air, together with the indoor and outdoor air's conditions, such as temperature, density, and heat capacity, then dictate the amount of heat flowing through the doors due to the air leakage. (Equation B4 shows how to calculate the total heat flow).

The displaced heat, or thermal energy, must be offset by the building's heating or air-conditioning equipment in order to keep the temperature inside the building at desired level. For example, during the winter, cold outdoor air leaks through the doors into the building and forces warm air of equal volume out of the building. To keep the building warm, the heating equipment must supply thermal energy, to the inside air, equal to the energy contained in the warm air that leaks out. In addition, since the equipment always has less than 100% efficiency, it must consume more energy than what it needs to supply.

[20] As suggested by Robert Cunkelman, senior engineer at MIT Department of Facilities.

To get a better sense of how much the energy consumption is, it is converted to i) the number of single-family houses that can be heated for a year[21] [22], and ii) the duration the a 100W light bulb can be powered. Additionally, using a simple multiplying factor based on statistics of greenhouse gas emission of specific fuels, the amount of CO_2 emission due to the air leakage through the doors can be estimated.

Calculation Result

The equipment in this study is assumed to be 60% efficient. Using the air leakage rate obtained from the previous calculation, it is estimated that, to heat and cool the air leakage through the doors (both swing and revolving combined) of building E25 in one year, *98,912.8* kilowatt-hour (kWh) of energy is required. That energy is enough to heat *6.5* single-family houses in one year, or to light a 100W bulb for *37.8* years. To generate that much energy, *18.8* tons of CO_2 is emitted.

It is interesting to see how much of this energy consumption could be saved if the revolving-door usage is higher than the present 23.3%. The calculations of the air leakages, associated energy consumption, and emissions are redone for revolving-door usage of 50%, 75%, and 100%. The annual energy consumptions and potential savings with respect to the current situation of different scenarios are shown below.

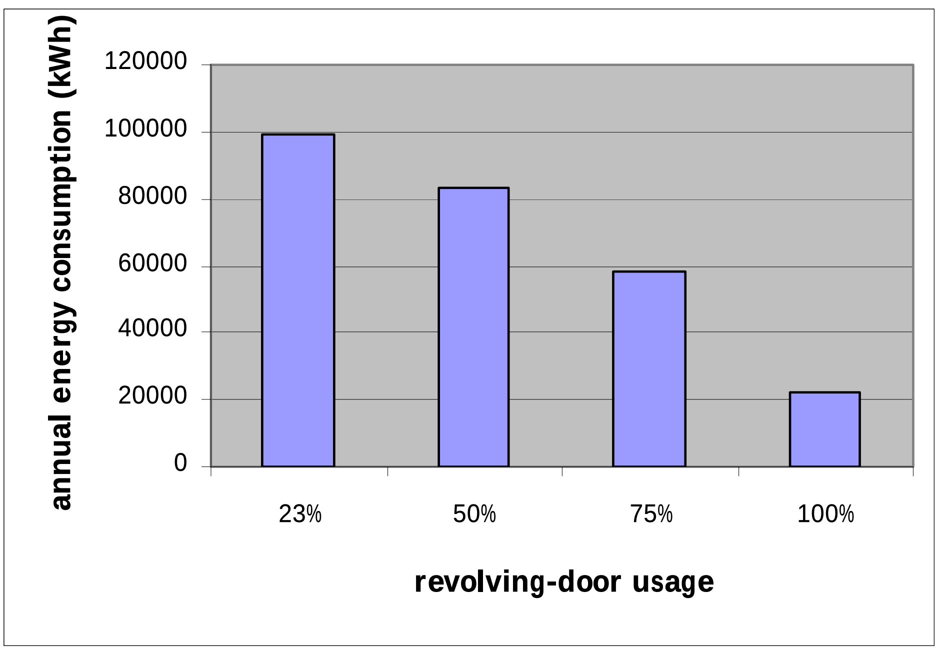

Figure 15. Annual energy consumptions due to air leakage through building E25's doors in different revolving-door usage scenarios

[21] 51.5 million BTU (or 15104.8 kWh) is required to heat an average single-family house.

[22] Energy Information Administration. 18 November 2004. "2001 Residential Energy Consumption Survey: Household Energy Consumption and Expenditures Tables." 1 MAY 2006 <http://www.eia.doe.gov/emeu/recs/recs2001/detailcetbls.html>

Table 1. Potential savings in different revolving-door usage scenarios

Revolving-door usage	50%	75%	100%
Saving of annual energy consumption	14.5%	38.7%	74.0%
# of houses the saved energy can heat in one year	1.0	2.7	5.1
# of years the saved energy can light a 100W bulb	5.8	15.3	29.0
Tons of CO_2 prevented	3.0	7.7	14.6

Note that the relationship between the annual energy consumption and the revolving-door usage is not linear. Instead, it shows that the higher the number of people using revolving doors, the more effective the incremental changes.

10.3. ENERGY COST AND PAYBACK TIME ESTIMATION

The air leakage and the energy consumption during the winter are higher than the annual average, as mentioned earlier. (The average air leakage from December to March is 3590.4 cfm, compared to the annual average of 2949.6 cfm). Consequently, the energy costs during the winter can be expected to be the highest as well. Therefore, the winter time provides the best window of opportunity for implementing habit-enforcing schemes, such as signage posting, with the quickest payback time.

Calculation Result

The average daily cost of energy due to the air leakage through building E25's doors is $13.10 during the winter[23]. If the revolving-door usage is increased to 50%, 75%, and 100%, that cost will reduce to $11.01, $7.66, and $2.83, respectively. The relationship between the revolving-door usage and the daily winter energy cost is shown below.

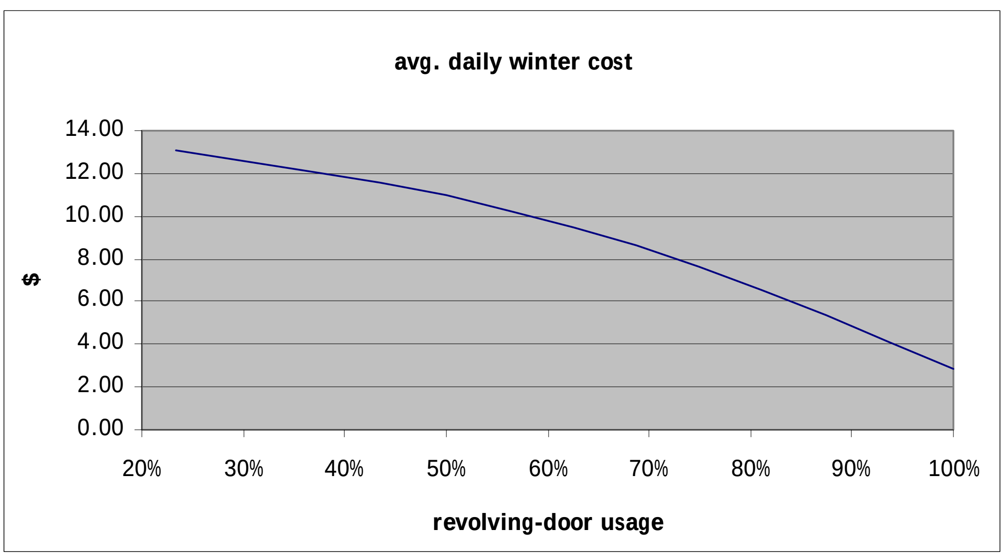

Figure 16. Average daily winter energy cost as a function of revolving-door usage

[23] Based on the wholesale cost of natural gas of $0.67/therm, as of May 8, 2006

The results from the signage study can then be mapped onto this graph to see the effectiveness of the different signs in terms of the daily heating cost reduction, as shown in the figure below.

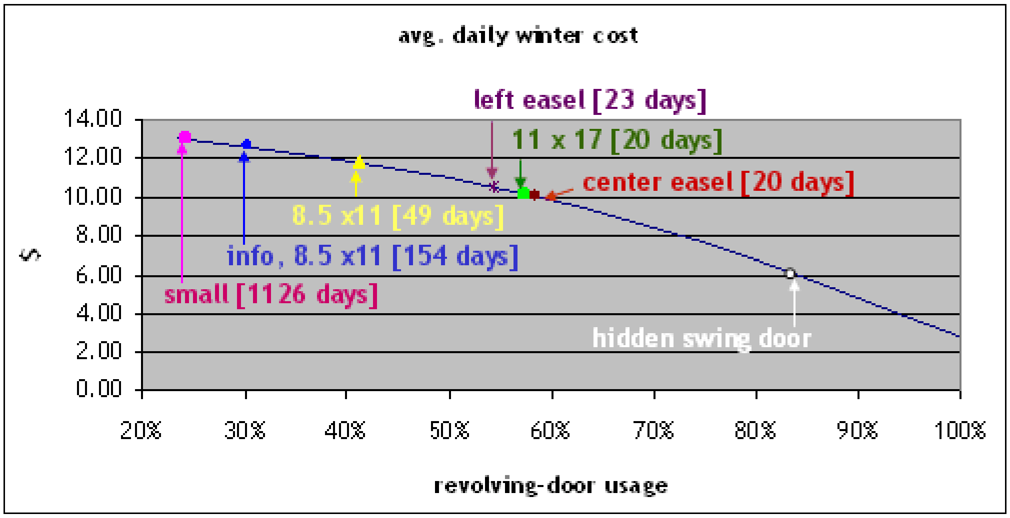

Figure 17. Daily winter energy cost reductions and payback times (in brackets) by different habit-reinforcing schemes

The 11"x17" sign and the sign on an easel placed at the center of the doors can reinforce the revolving-door usage up to about 58% and reduce the daily winter energy cost down to about $10. Assuming that the sign costs $60, the investment will be paid back in only 20 days. Moreover, even though the saving of $3 per day may seem small, the energy saving associated with the increased revolving-door usage is over 20% and is enough to heat 1.5 single-family houses for a year. Also, note that the daily winter energy cost can be reduced even more with other habit-reinforcing schemes, such as "hiding" the swing door, which can increase to the revolving-door usage to well over 80%. Thus, the schemes that result in seemingly small habit changes also have great implications in a larger scale.

11. FUTURE STEPS

The interpretation above reveals that the door use study has the ability to contribute to the ongoing efforts to create an increasingly sustainable environment. A number of next steps are appropriate, given the framework and results of the revolving door use study on the MIT campus.

1) *Publish the findings.* A number of publications that may be interested in the study have been identified. A report of our experiment and results will be sent to these publications. These publications include:
   - Energy and Environment (an MIT publication)
   - Energy and Buildings
   - Building and Environment
   - Environment and Behavior

2) *Forward information to MIT Student Groups and MIT Practicums.* Many student organizations on campus are dedicated to sustainable development and energy conservation. These groups include the MIT Energy Club, the Sloan Energy and Environment Club, the Innovation Club, Share a Vital Earth, and Students for

Global Sustainability. In particular, the last group, an organization "committed to sustainable development and conservation on both the global and local levels," has shown a dedication to implementing change on the MIT campus.[24] The group is behind a number of conservation projects on campus – they produced Studio!Sus, a brochure about integrating sustainability into the everyday life of people in Cambridge, as well as the energy conservation campaign entitled, "Do the bright thing: when not in use, douse the juice." The information may also be useful to MIT practicums, project-based courses that are a part of MIT's Department of Urban Studies and Planning curriculum.

A number of options are available for potential practicum and student groups. One project group might stick with the signage campaign and try different messages on the signs pertaining to different areas of possible energy conservation. Another project group might have the means to try one of the different approaches to habit change discussed earlier in this report before the methodology section. Additionally, the concept of habit modification could be used to implement another local project that can make a global difference. By offering recommendations and guidance to these groups, the work done in this study can be related to broader implications for energy conservation on campus.

3) *Involve the MIT Administration in implementing signage on campus.* While the study has focused on enacting change through grassroots efforts, a top-down approach can also be used to implement change. It is possible to try and increase revolving door use through an approach based on the efforts of the MIT administration. This approach would involve head decision-makers at MIT, primarily those in the Facilities Department. However, two factors should be accounted for if any attempt is made to move forward using this administrative approach.

Firstly, the official approval process for the implementation of signage at MIT is, for the most part, unclear. Peter Cooper, MIT Manager of Sustainability Engineering and Utility Planning, has indicated that a building's location on campus would probably play a role in the type of signage review needed. The process required to approve signage for placement on or in front of Building 66, for example, would be more extensive than the review process required for the Tang Center (E51) because Building 66 has a greater amount of pedestrian traffic and is located in an area with a higher profile than the Tang Center. MIT's receptiveness to looking over new signage designs and its willingness to provide guidance through the ambiguous review process indicate that an opportunity exists for signage implementation to occur through a top-down process.

Secondly, the Facilities Department considers the aesthetic quality of buildings of equal importance to energy savings. Large, unattractive revolving door use signs on buildings, despite their success in achieving greater energy conservation, would have a negative impact on the built environment, a trade-off not desired by Bill Anderson, MIT's Chief Facilities Officer. Interest expressed by Mr. Anderson in the revolving door signage displayed in Tech Square, specifically the signage on movable stands, indicates that a tasteful middle ground combining aesthetics and energy conservation can be achieved at MIT.

[24] "Students for Global Sustainability." 21 April 2006. Students for Global Sustainability. 7 May 2006. <http://openwetware.org/index.php?title=Students_for_Global_Sustainability_Wiki>.

4) *Involve the MIT Administration in initiating additional signage campaigns beyond door use.* If the MIT administration implemented revolving door use signage across campus and obtained sizeable energy savings, expansion of this energy conservation program should be considered. Such a program could bring energy conservation signage into other aspects of life at MIT. Since the primary signage design for revolving door use centered on the phrase "Please Use the Revolving Door," new catchphrases could encourage MIT students, faculty, staff, and visitors to make additional efforts to achieve energy savings. Possible additional messages on signage include:

- Please Print Double-sided
- Please Turn Off the Lights
- Please Close the Fume Hood
- Please Turn Off Computers Upon Leaving

This broad use of signage could help create a culture of sustainability on campus, thereby reducing MIT's negative impact on the environment and providing the school with considerable financial savings.

12. CONCLUSION

The purpose of the revolving door usage study was to understand how habits could be modified into "green habits." The study was implemented using methods respectful of sustainable actions that have already taken place on the MIT campus, which would make it more feasible to engage groups on campus enthusiastic about implementing change in similar projects.

It is possible to make three concrete conclusions from the results and interpretations. Firstly, an effective means of changing habits was identified. Large signs, especially those on easels in front of doors, significantly modify behavior and influence people to use revolving doors instead of swing doors. Secondly, the interpretations show that substantial energy is saved when people use the revolving doors – the smallest of habit changes contributes to energy conservation. Lastly, the study showed that habits are reinforced by design.

In order to understand the significance of these conclusions, it is necessary to turn back to the initial question that sparked the project and formed the theme of the class: Can local changes make a global impact? The study shows that the modification of one habit, a seemingly small change, indeed has the ability to eventually impact the environment on a global scale. This result verifies that a number of issues should be engaged at the habit level to increase the amount of energy saved. Most importantly, the study clarifies a very important fact: the larger the number of people that modifies their habits, the greater the global impact. That is, the ratio of people that modifies their habits to the amount of energy saved does not increase linearly – when more and more people begin to use the revolving door, the amount of energy saved increases exponentially. Thus, while it is clear that local changes can make a global impact, it is crucial to create a culture of energy conservation that influences more and more people to change their habits towards sustainability in order to maximize the impact that can be made by these small changes.

13. ACKNOWLEDGEMENTS

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Peter Cooper, Manager of Sustainability Engineering and Utility Planning, MIT Department of Facilities

Robert Cunkelman, Senior Engineer, MIT Department of Facilities

David McCormick, Director of Operations, MIT Department of Facilities

Laxmi Rao, Information and Technology Project Manager, Department of Information Services and Technology

Lakhan Verma, Senior Engineer, MIT Department of Facilities.

14. APPENDIX

APPENDIX A: Revolving Door Images

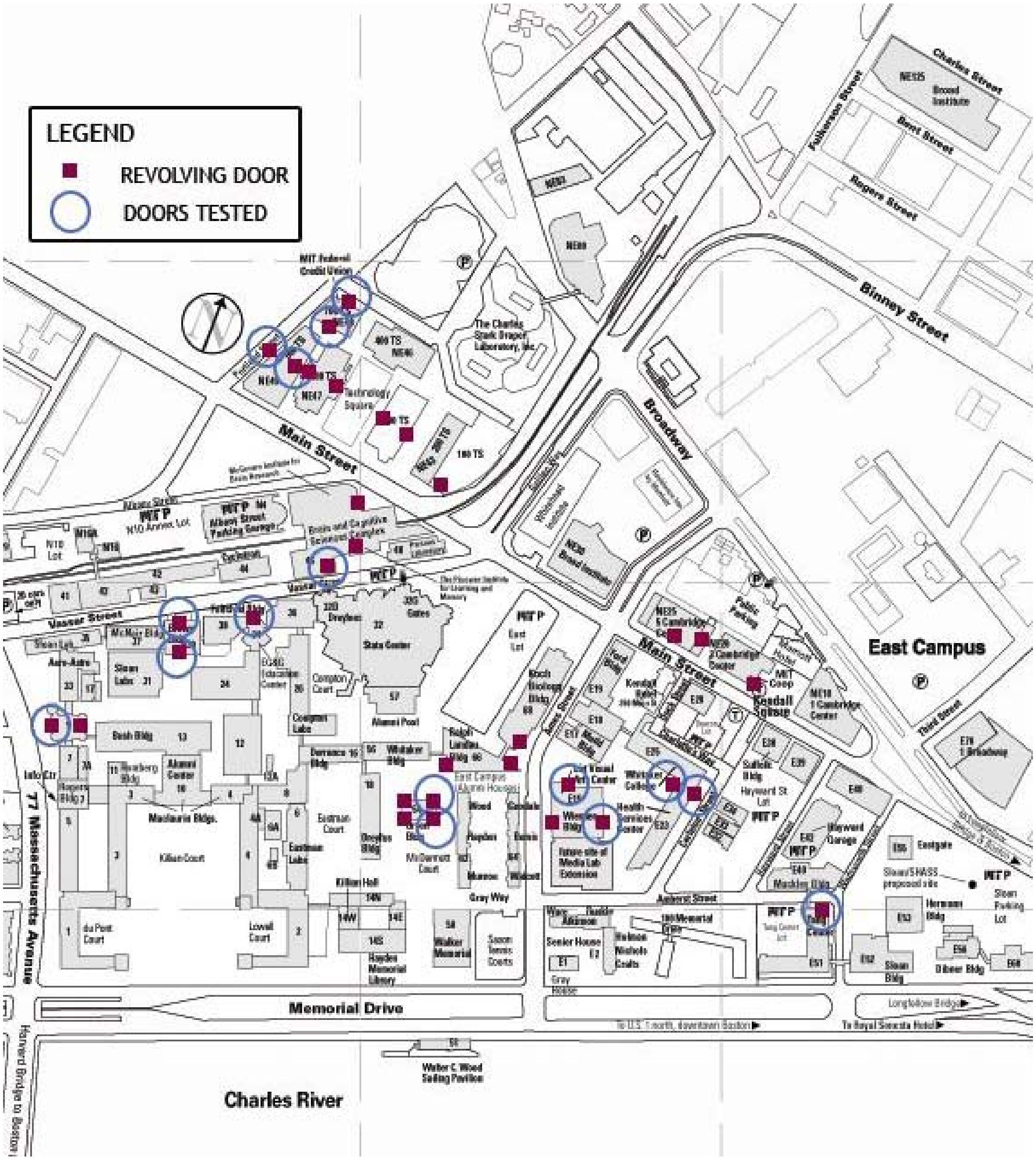

Figure A1. Map of MIT campus with building numbers. Revolving doors on campus are represented by the magenta blocks. The blue circles represent the revolving doors examined in this study.

Figure A2. E15 (1) - Door facing E23.

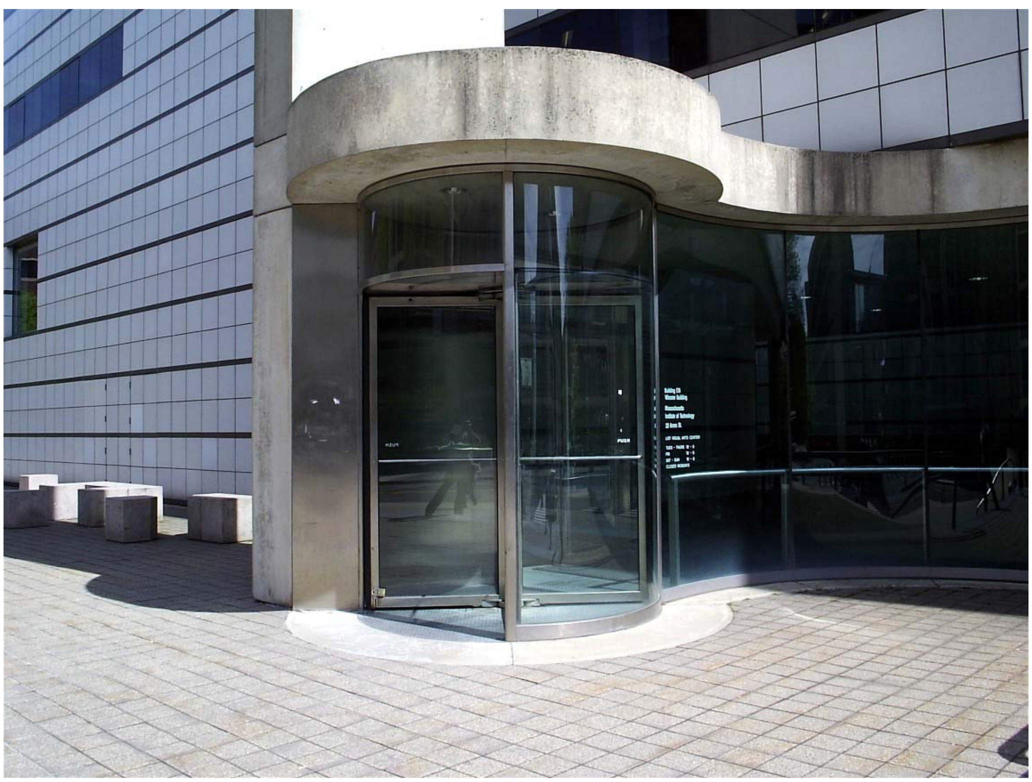

Figure A3. E15 (2) - Door facing the main campus.

Figure A4. E25 (1), Carlton Street side - Door view for a user approaching from subway station.

Figure A5. E25 (2) - View from a user approaching from the main campus.

Figure A6. E51 (Tang Center) - Corner door.

Figure A7. NE48 (700 Tech Square) - Courtyard side.

Figure A8. NE49 (600 Tech Square) - Courtyard side.

Figure A9. Building 9 - Massachusetts Avenue side.

Figure A10. Building 34 -Vassar St. side.

Figure A11. Building 39 - Vassar Street side.

Figure A12. Building 46 (Brain and Cognitive Science Building) - Vassar Street side.

Figure A13. 54, northeast corner - View of users approaching from the main campus.

Figure A14. Building 66, corner – Ames Street side.

APPENDIX B

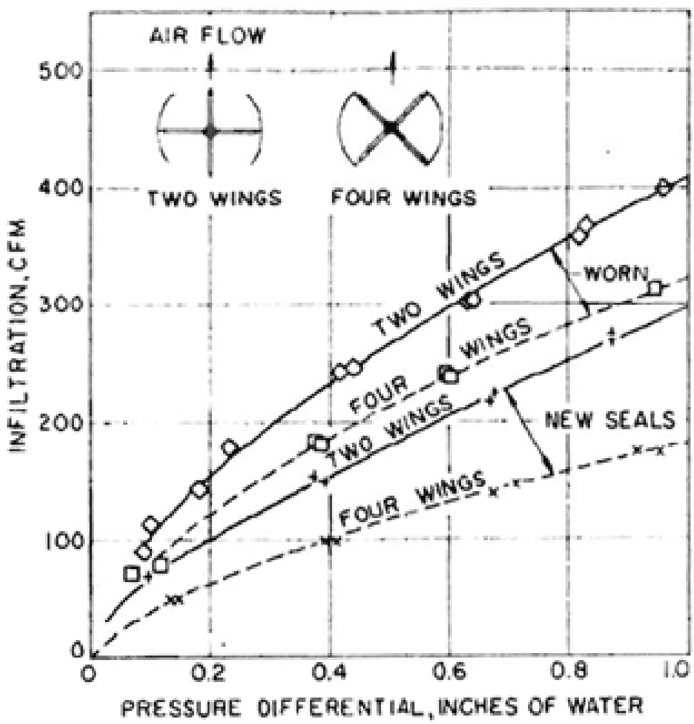

Figure B1. Infiltration through new and worn door seals (door not revolving).[25]

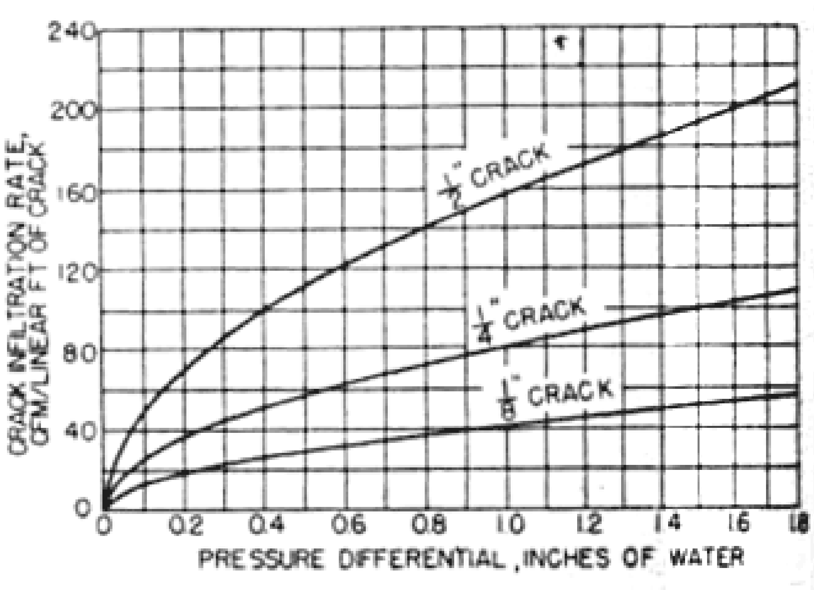

Figure B2. Infiltration through door cracks (door not revolving).[26]

[25] Schutrum, L. F., et al. 43-50.
[26] Min, T. C. 121-128.

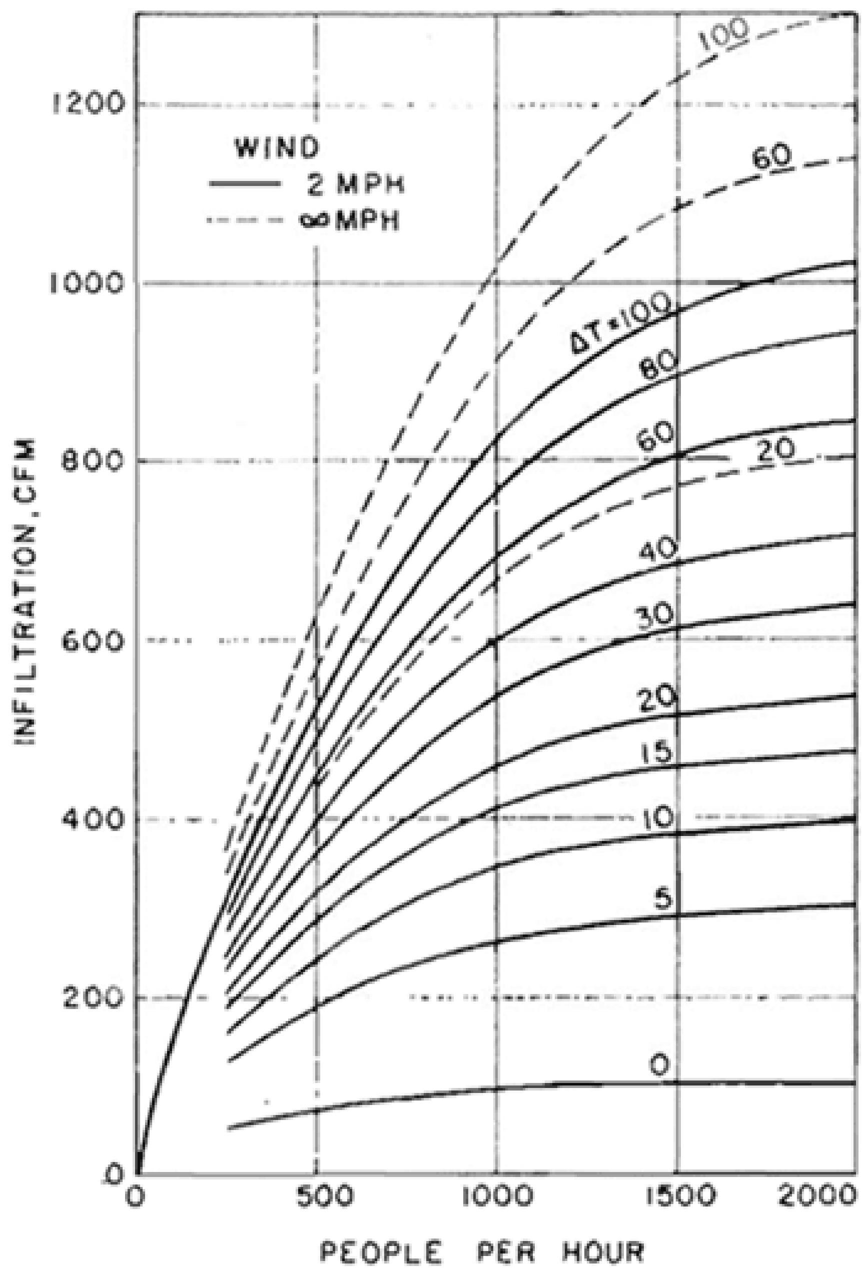

Figure B3. Infiltration through manually operated revolving door (air movement 35 fpm indoors, air leakages past door seals deducted).[27]

[27] Schutrum, L. F., et al. 43-50.

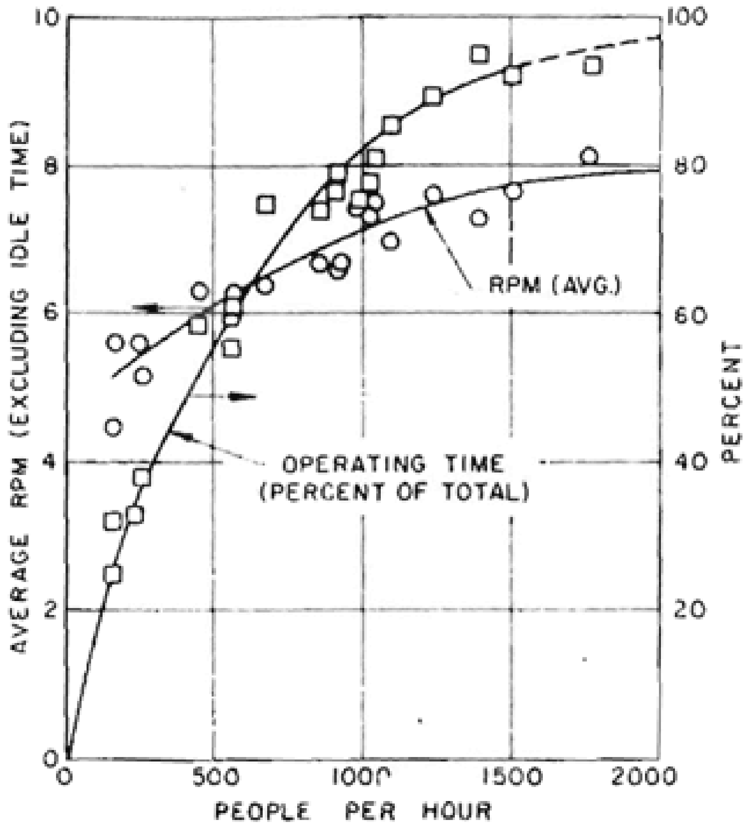

Figure B4. Operating time and averaged rpm vs. traffic rate of manually operated revolving door.[28]

[28] Schutrum, L. F., et al. 43-50.

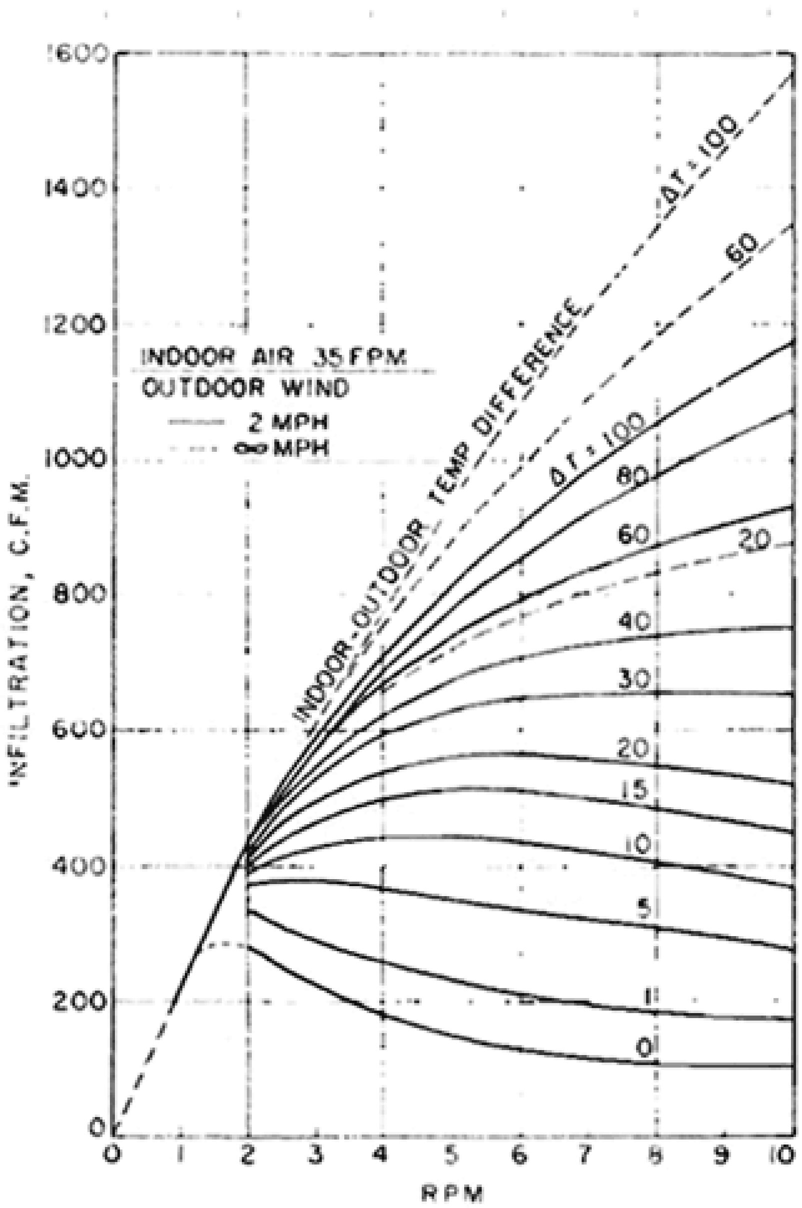

Figure B5. Infiltration vs. rpm and indoor-outdoor air temperature difference (air leakages past door seals deducted).[29]

[29] Schutrum, L. F., et al. 43-50.

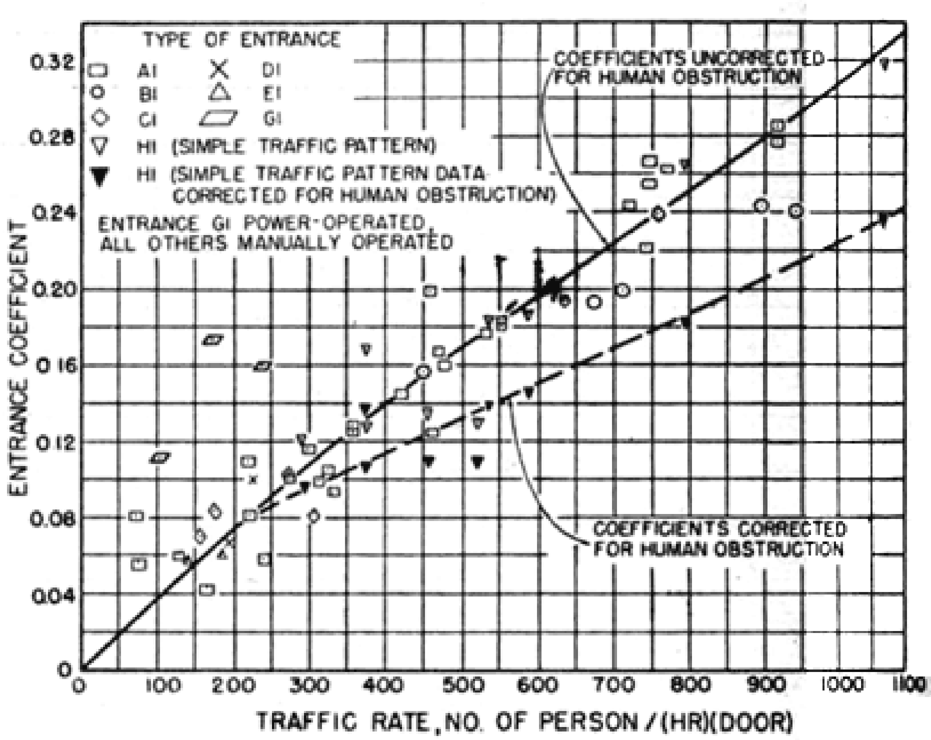

Figure B6. Entrance coefficients for single-bank entrances.[30]

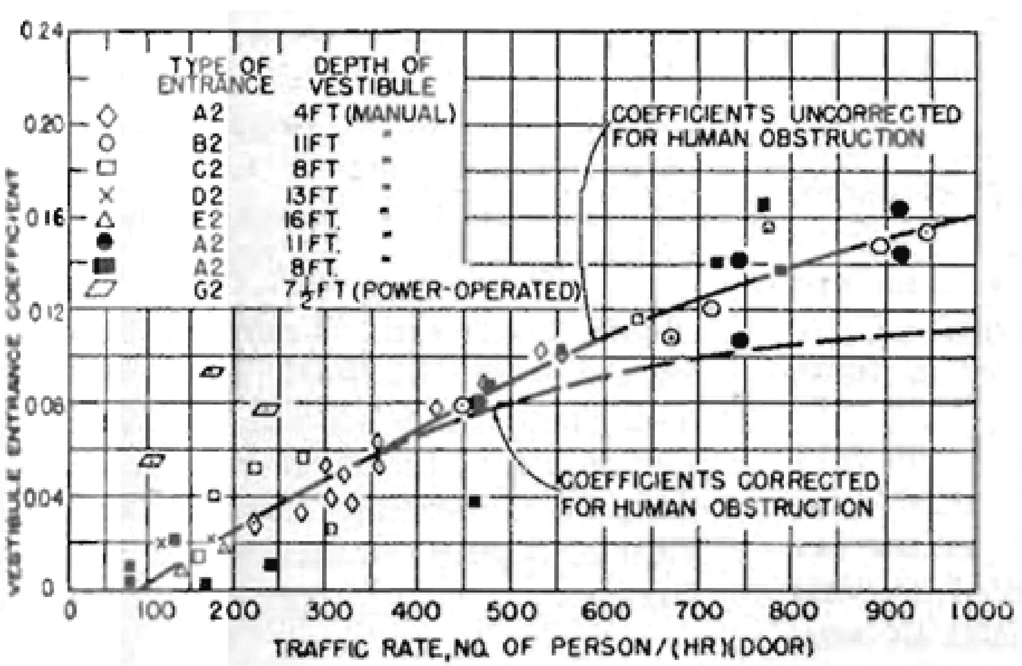

Figure B7. Entrance coefficients for vestibule entrances.[31]

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[30] Min, T. C. 121-128.
[31] Min, T. C. 121-128.

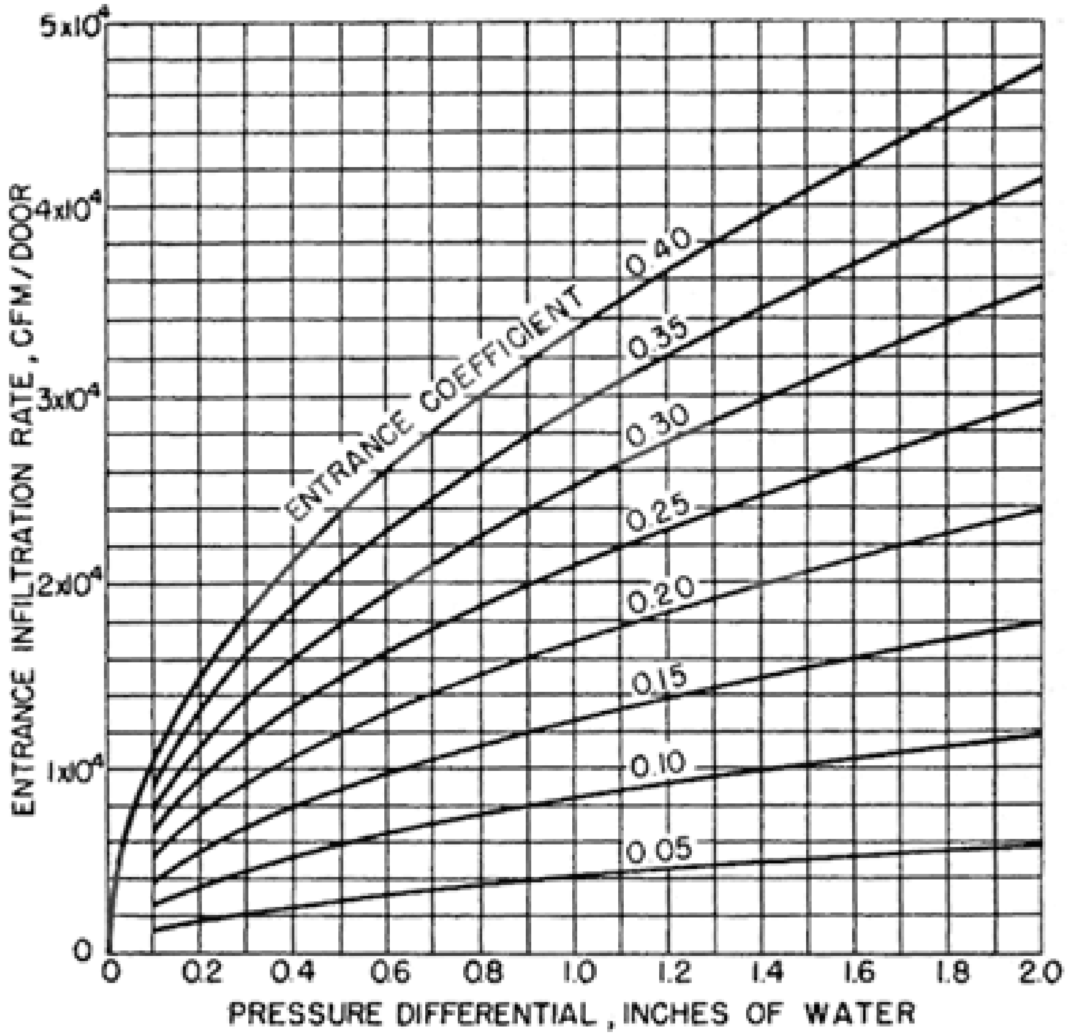

Figure B8. (Swing-door) entrance infiltration rate for various pressure differentials and traffic rates.[32]

[32] Min, T. C. 121-128.

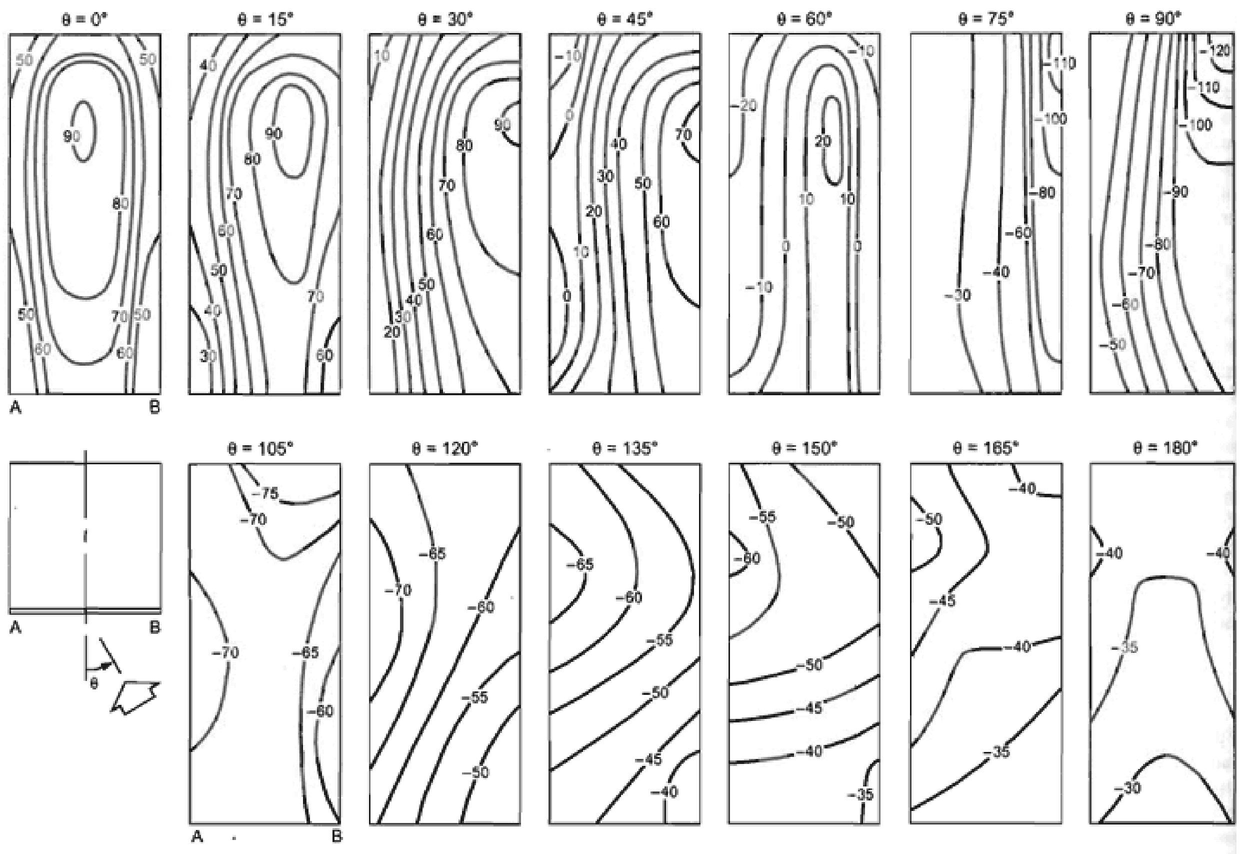

Figure B9. Local pressure coefficients (C_p x 100) for tall building with varying wind direction.[33]

[33] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

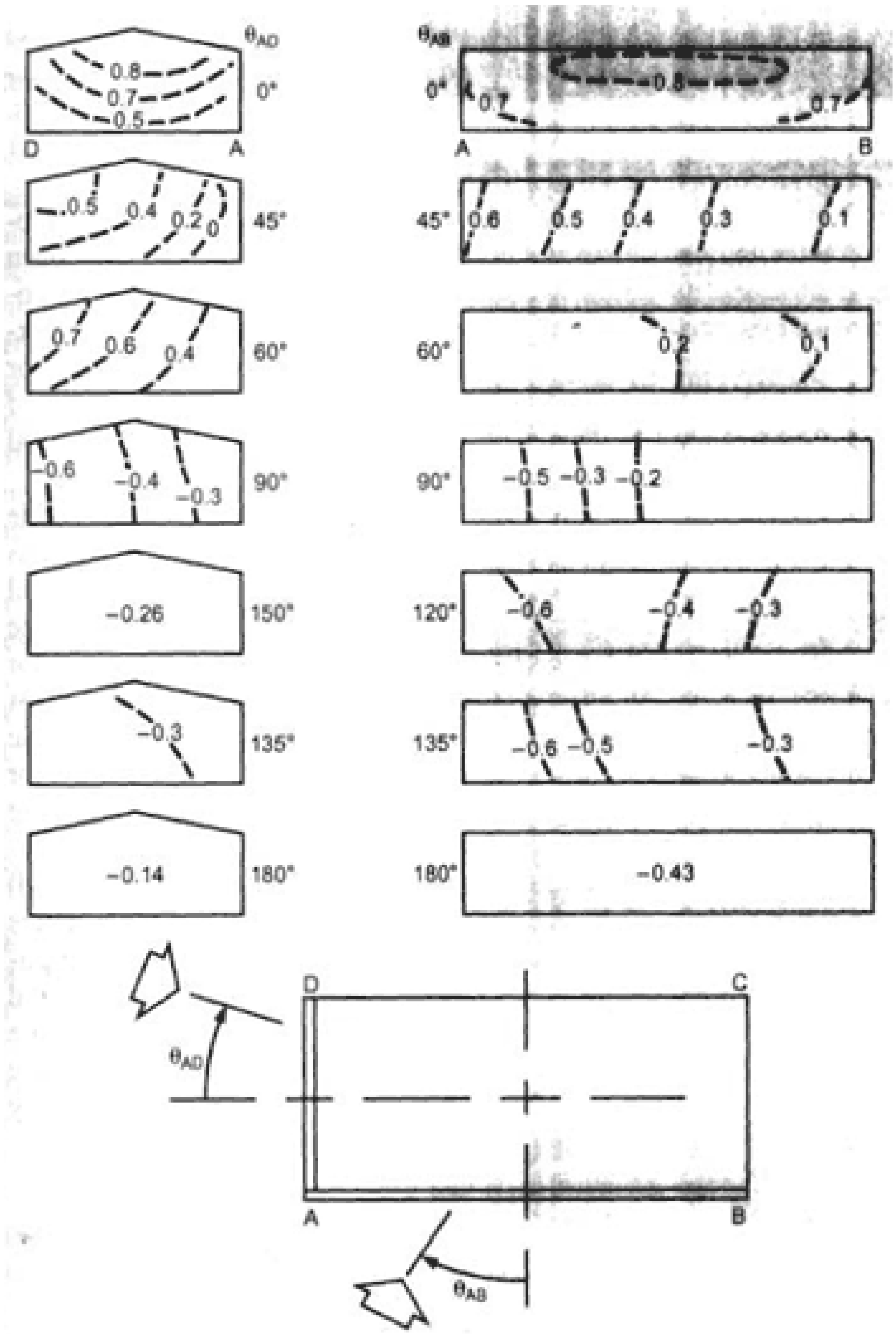

Figure B10. Local pressure coefficients for low-rise building with varying wind direction.[34]

[34] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

APPENDIX C

Total pressure differential, Δp (in. of water):

$$\Delta p = p_w - \Delta p_s \quad \text{(C1)}$$

where

Δp_s = stack pressure difference, in. of water

p_w = wind pressure, in. of water

Stack pressure difference, Δp_s (in. of water):

$$\Delta p_s = C_1 \rho_o \left(\frac{T_o - T_i}{T_i} \right) g \left(H_{NPL} - H \right) \quad \text{(C2)}$$

where

C_1 = unit conversion factor = 0.00598 (in. of water)·ft·s^2/lb

ρ_o = outdoor air density, lb/ft^3

T_o = outdoor temperature, °R

T_i = indoor temperature, °R

g = gravitational acceleration = 32.2 ft/s^2

H_{NPL} = height of neutral pressure level, ft, may use ½ of the height of the building

H = height of the point of interest, ft, may use ½ of the height of the door

Wind pressure, p_w (in. of water):

$$p_w = C_2 C_p \rho \frac{U^2}{2} \quad \text{(C3)}$$

where

C_2 = unit conversion factor = 0.0129 (in. of water)·ft^3/lb·mph^2

C_p = wind surface pressure coefficient (see Figures B9 and B10)

ρ = outdoor air density, lb/ft^3 (about 0.075)

U = wind speed, mph

Heat transferred, E_{ht} (J):

$$E_{ht} = (T_i - T_o)\rho VC \tag{C4}$$

where

T_i = indoor air temperature (°C)

T_o = indoor air temperature (°C)

ρ = air density = 1.2929 kg/m^3

V = volume of air (m^3)

C = heat capacity = 1.03 * 10^3 J/kgK

APPENDIX D

Table D1. Weather data of Boston, MA from April 2005 to March 2006.[35]

Month	Avg. High Temperature (°F)	Avg. Wind Speed (mph)
Jan	43	12
Feb	38	13
Mar	47	12
Apr	58	11
May	58	11
Jun	77	10
Jul	81	10
Aug	82	9
Sep	76	10
Oct	61	13
Nov	54	11
Dec	38	12

[35] The Weather Underground, Inc. 2006. "History for Boston, Massachusetts." 1 May 2006 <http://www.wunderground.com/>.

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Fig. 3-5: Revolving doors on the MIT campus. Personal photograph by group. 08 May 2006.

Fig. 6-7: Signage created for study by group. Revolving door image on top right from "Revolving Door Working Group." 2006. Revolving Door Working Group. 31 March 2006 <http://www.revolvingdoor.info/>.

Fig. 8: E25 revolving doors examined in study, modified by group using "Campus Map." Massachusetts Institute of Technology. 12 May 2006 <http://whereis.mit.edu/map-jpg>.

Fig. 9: Revolving doors on the MIT campus. Personal photograph by group. 08 May 2006.

Fig. 10: Results of study.

Fig. 11: Revolving doors on the MIT campus. Personal photograph by group. 08 May 2006.

Fig. 12-17: Results of study.

Fig. A1: All revolving doors examined in study, modified by group using "MIT Campus Map." Massachusetts Institute of Technology. 12 May 2006 <http://web.mit.edu/campus-map/pdf/campusmap06.pdf>.

Fig. A2-A14: Revolving doors on the MIT campus. Personal photograph by group. 08 May 2006.

Fig. B1: Schutrum, L. F., et al. "Air infiltration through revolving doors." ASHRAE Journal 3.11 (1961): 43-50.

Fig. B2: Min, T. C. "Winter infiltration through swinging-door entrances in multi-story buildings." Heating, Piping and Air Conditioning 30.2 (1958): 121-128.

Fig. B3-B5: Schutrum, L. F., et al. 43-50.

Fig. B6-B8: Min, T. C. 128.

Fig. B9-B10: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2005 ASHRAE Handbook: Fundamentals. Atlanta: ASHRAE, 2005.

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