Potential Energy Savings on the MIT Campus

By

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ABSTRACT

The MIT community and the City of Cambridge embarked on initiatives to reduce energy consumption and Greenhouse Gas emissions in accordance with the Kyoto Protocol which calls for a 20 % reduction in 1990 levels of GHG emissions by 2010. This thesis seeks to expand our understanding of how the MIT campus consumes energy and with that knowledge recommend methods of reducing energy consumption by eliminating irresponsible energy use. Based on the GHG emission map created by Tiffany Groode in her 2004 thesis *A Methodology for Assessing MIT's Energy Use and Greenhouse Gas Emissions,* the second largest energy consuming building per square foot, Building 18, was selected and analyzed in detail. This thesis proves the high hood density, lack of an exhaust heat recovery system, and irresponsible fume hood use necessitate Building 18's wasteful consumption of energy. Research revealed that, on average, 67 hoods were left open at night, and 88 were open during daytime use. Of those open hoods, only 5 were in use during the night, and 48 were in use during the day. If the unused hoods were closed the consumption of electricity, steam, and chilled water could be decreased by approximately 17% and save the Institute $350,000 a year in utility costs.

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Chapter 1: Introduction

1.1 Motivation

Advances in affordable sustainable energy technology are currently outpaced by increasing demand for energy resources. Technological advances alone will not stem increasing greenhouse gas emissions in the near term. Significantly reducing irresponsible energy consumption could mitigate the increasing demand and its environmental impact. Residential and commercial buildings devour 39 percent of all energy consumed in the United States; transportation activities only consume 28 percent of the total. MIT, a world leader in technology, seeks to lead by example and reduce our campus energy consumption with the Walk the Talk initiative. Existing research by Tiffany Amber Groode in her 2004 MIT masters thesis *A Methodology for Assessing MIT's Energy Use and Greenhouse Gas Emissions* identified laboratories as the largest energy sinks.

1.2 Energy Consumption on the MIT Campus

The dominant mode of energy consumption on the MIT campus is utilities; transportation accounts for less than 10 percent of the yearly total. The Co-Generation plant provides the campus with steam, chilled water, and electricity supplemented by N Star. Laboratory buildings consume over 70 percent of campus utilities. MIT's laboratories exhibit high energy consumption per square foot due to plug loads, upgraded lighting systems, and intensive HVAC systems to protect researchers from noxious materials. MIT documents the distribution of utilities from the Co-Gen plant to its client buildings, but the Facilities Department does not have the staff to identify irresponsible energy consumption. The goal of this research is to provide that information.

All of MIT's 162 buildings connected to the Co-Gen plant are ranked yearly for their total energy consumption normalized by square footage. Building 39 is the perennial number one energy hog due to the high concentration of clean rooms. The sterile clean room environment necessitates a large electrical load which powers oversized air handlers and air filtration systems. The air forced through the filtration system is also conditioned (dehumidified and heated or cooled) then this processed air is exhausted rapidly. Because of the highly noxious quality of the chemicals used in these facilities, the air cannot be recycled so the energy imparted to the processed air is lost.

Total energy consumption by MIT's buildings is ranked via a sum of equivalent MBTU of energy for metered use of chilled water, steam, and electricity. The Department of Facilities has developed a conversion factor for the conversion of natural gas energy into electricity. The conversion factor incorporates the efficiency of the turbine generator and distribution losses. The energy transfer from natural gas to electricity is about 30 percent efficient but much of the lost energy is used to generate steam in the Heat Recovery Steam Generator. The total efficiency of the Co-Gen plant is about 75 percent[1].

$$1\ KWH = 10{,}000\ BTU$$

Equation 1: MIT's Energy Conversion for Accounting Purposes

The Dreyfus Building, Building 18, is the home of the Chemistry Department and is the second largest consumer of energy on the MIT campus per square foot per year. Construction of the I.M. Pei designed building began in 1968 and was finished in 1969. The building underwent a major renovation beginning in 2001 finished 2003 by Goody Clancy. The newly renovated

[1] Groode, T. *A Methodology for Assessing MIT's Energy Use and Greenhouse Gas Emissions.* May 2004

building went from fifth on MIT's list of energy consumers to second due to the addition of an extremely high exhaust hood density and the lack of heat recovery in the building's exhaust.

The MIT campus draws a relatively constant 26 Megawatts of electrical energy most of which is produced by the 21 Megawatt combustion turbine in the Co-Gen Plant. The campus-wide electrical load varies by approximately 3-4 Megawatts from day to night, and though rated at a 21 megawatt output the Co-Gen turbine regularly outputs 24 Megawatts of electrical power according to the MIT Department of Facilities. The Co-Gen plant can be powered by No. 2 oil or natural gas. Due to the lower emissions of natural gas the plant has burned natural gas exclusively for the past few years, despite the higher cost.

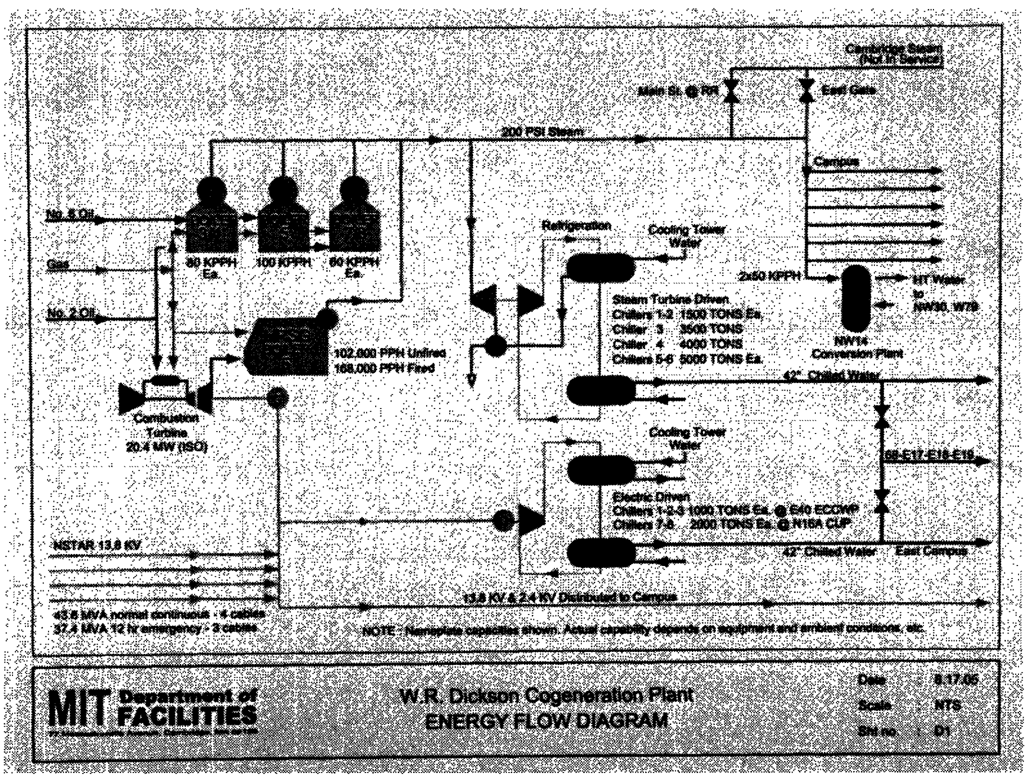


Figure 1: Cogeneration Plant Energy Flow Diagram
(Courtesy of the Department of Facilities)

Due to the linked cycle of the Co-Gen plant's combustion turbine and heat recovery steam generator, it is difficult to attribute an exact cost for the electricity and steam generated.

For accounting purposes the Facilities Department determined a reasonable approximation of $0.115 per kilowatt-hour for electricity and $14.30 per 1000 pounds of steam produced. The Co-Gen plant drives chillers 1-3 with steam and electricity, 4-6 with steam, and 7-8 with electricity. The chillers supply the campus' chilled water demand.

1.3 Background In Climate Change Science

The growth in worldwide production of greenhouse gas threatens to destabilize the earth's environment. On May 3rd 2006 the White House Council on Environmental Quality released a statement, reversing their stance of denial, that environmental changes since the 1950's have shown an increase in the temperature of the earth's surface and the low and mid atmosphere. The report admits that these changes can not be explained by natural process alone and must be influenced by human action. Furthermore, the National Oceanic and Atmospheric Administration stated on May 1st 2006 that Carbon Dioxide and Nitrous Oxide levels in the atmosphere are still growing.

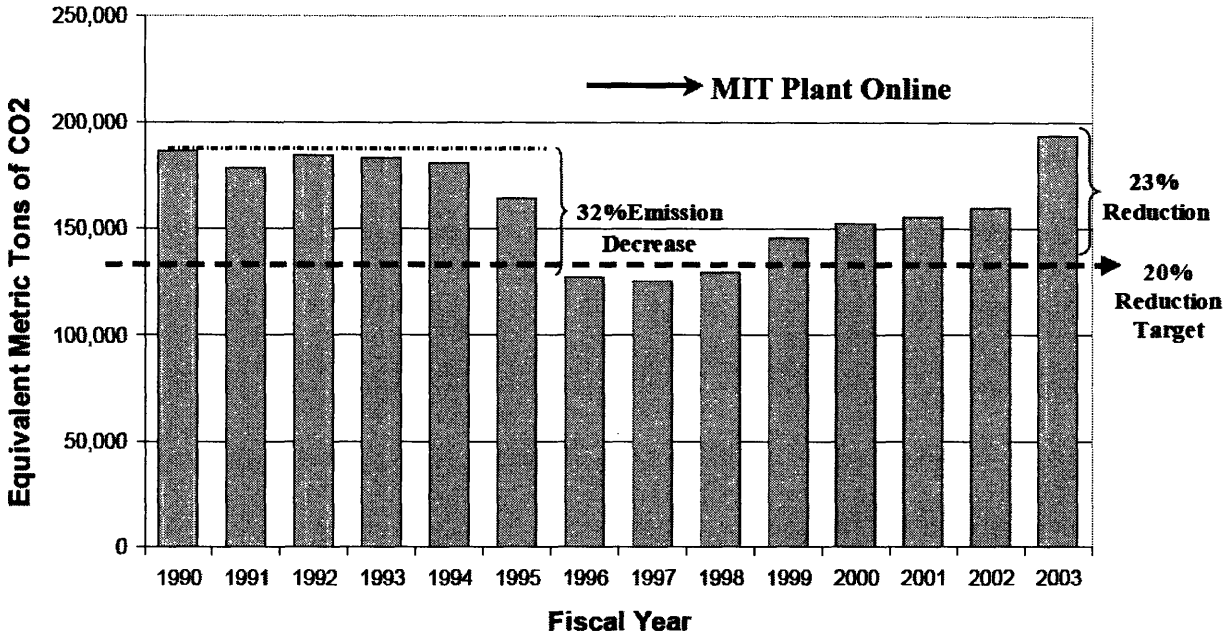


Figure 2: MIT's CO_2 Production by Year
(Courtesy of Tiffany Amber Groode)

The largest component of MIT's GHG emission is carbon dioxide from operation of the Co-Gen plant. The distant second is nitrous oxide at a rate of 800 equivalent metric tons of CO_2 per year. As shown in the above graph carbon dioxide emissions are continuing to increase due to increased demand for utilities and expansion of the MIT campus. The Co-Gen plant came online midway through 1995 causing the sharp drop in equivalent carbon dioxide emissions. In order to reach the reduction set out in the Kyoto Protocol, MIT will have to decrease GHG production by over 23 percent[2].

The Kyoto Protocol has set a challenge to its member nations, which the United States of America is not, to reduce the total Greenhouse Gas (GHG) emissions to 20 percent below the levels recorded in 1990 by the year 2010. Though the United States is not a member of this treaty the City of Cambridge has imposed this important pollution reduction upon itself. As global citizens it is dearly important to research and implement the necessary advances in

[2] Tiffany Groode *A Methodology for Assessing MIT's Energy Use and Greenhouse Gas Emissions* 2004

technology and modify our energy consumption behavior. Possible avenues to reduce GHG emissions are increasing efficiency in our production of energy, and decreasing overall consumption through mindful conservation and reduction of excess in our daily lives.

MIT has developed an initiative under current president Susan Hockfield known as the Walk the Talk program. It is supposed that MIT seeks to set the example for our greater community of the United States and then the world in meeting or beating the stipulations set down in the Kyoto Protocol, all the while researching further into renewable energy and more efficient methods of consumption.

Fiscal Year 2003 Data			
	MIT Campus Building Square Feet	**Number of MIT Buildings**	**% Of Total Campus Square-Feet**
Lab	5.825.683	89	55.5%
Office	2,360.828	47	22.5%
Housing	2,316.068	26	22.1%
Total	10,502,579	162	100.0%

Table 1: MIT Building Square footage by Purpose
(Courtesy of Tiffany Amber Groode)

Tiffany Groode's thesis mapped MIT's campus-wide GHG emission and as such indicates important areas to reduce consumption. Groode's work has indicated the numerous MIT laboratories as the largest energy users: it logically follows that the laboratories have the highest potential yield of energy savings from better consumption habits and techniques. The following table indicates how MIT produces GHG on the macro scale, and indicates that laboratory space is far and away the largest producer of these pollutants.

Fiscal Year 2003 Collected Data						
	MIT Campus Building Square Feet	Number of MIT Buildings	% Of Square Footage Analyzed	Energy Use per Square-Foot (MMBTU/sq-ft type)	CO_2 Emissions per Square Foot (Metric Tons CO_2 / sq-ft type)	CO_2 Emission (Metric Tons of CO_2)
Lab	2,002,824	21	34.4%	0.387	0.030	60,362
Office	1,327,566	20	56.2%	0.159	0.013	16,991
Housing	2,077,927	14	89.7%	0.123	0.010	20,980
Total	5,408,317	55	51.5%	-	-	98,333

Table 2: Green House Gas Emissions by Building Type
(Courtesy of Tiffany Amber Groode)

Groode's assessment of energy use by building type in the above table was based on MIT's internal energy consumption audits. Office buildings and dorms were examined in greater depth than labs. The *% of square footage analyzed* figure is normalized by the total square footage of that building type on campus. Variability in energy consumption by housing and office buildings is significantly less than laboratories because the needs of dormitories and office space are relatively uniform. Labs, on the other hand, vary greatly in terms of purpose and equipment used which leads to large disparities in power consumption between a computer lab and a chemistry lab. An assessment of less than 35 percent of total laboratory square footage on campus is not enough to characterize the energy consumption behavior of lab space at MIT. Tightly defined laboratory subgroups, dictated by purpose and equipment used, are needed.

Chapter 2: Building 18 Energy Balance

2.1 Scope of Research

Being a single researcher it would be impossible to thoroughly analyze the energy consumption of the entire MIT campus in great detail, or a multitude of specific buildings. As such it was clear that a thorough analysis of a single model building with the greatest detail and resolution would have more benefit in the fight for a significant reduction in overall campus energy consumption. Examining laboratory buildings should present the greatest potential savings in energy consumption. Considering the official MIT energy consumption rankings, it also is logical to start with the worst, learn from analyzing those buildings, and then apply the knowledge gained from them to buildings which consume significantly less energy in a process of continual learning and implementation.

Building No.	Building Name	Building Type	EUI (KBtu/sq ft/yr)	CO_2 / sq ft (Metric Tons)
39	Stanley Gordon Brown Building (Information Processing Center)	Academic	2,279	68
18	Camille Edouard Dreyfus Building	Academic	1,034	31
E17	Seely G Mudd Building	Academic	999	30
68	Biology Building	Academic	950	28
13	Vannevar Bush Building	Academic	943	28

Table 3: Top 5 Energy Consuming Buildings at MIT

Building 39 is the largest consumer of energy per square foot on campus. The design, layout, and purpose of Building 39, with its high concentration of clean rooms, requires a high fixed energy consumption. In other words, Building 39's minimum energy consumption for meaningful operation is large. Though the air is only cycled once through the clean room and then exhausted, the expelled air does pass through a heat recovery system before being dumped to the external environment. Building 18, on the other hand, has the highest fume hood concentration on campus, lacks an exhaust heat recovery system, and is perennially illuminated, not unlike a Christmas tree. Buildings 18, E17, 68, and 13 all use fume hoods. Two of the top five consumers house operations for the Biology Department, 68 and E17, and Building 13 is home for the Center for Materials Science and Engineering.

Though Building 18 has the highest concentration of fume hoods there are many other buildings which use fume hoods as a necessary part of regular operation and could immediately benefit from analysis of a chemical laboratory's operation. Notable examples of similar buildings are the Biology buildings, the Materials Science laboratories and other chemical labs on campus.

To fully understand how an MIT laboratory consumes a large quantity of energy, all aspects of the building's operations need to be identified. Using a light meter, readings throughout Building 18 were taken every 30 feet and in the stairwells. Those meter readings were compared to similar readings taken in the Infinite hallway and the halls of Building 1 and 56. The measured lumens in Building 18 were a factor of two larger than the other halls observed. The electrical energy consumed by lights in the laboratory were observed on numerous dates from November 15, 2005 to April 3, 2006. The continuous operation of lights was captured with time lapse photography for a continuous period of 3 days to further support our hypothesis that the lights in Building 18 remain on during all hours of the day and night.

The heating and electrical systems were observed with the help of Robert Cunkelman of the MIT Department of Facilities and Peter Cooper of the same department. Their supervision facilitated the exploration of the steam and chilled water flow rates into the building, the airflow through the exhaust hoods and air handlers, and the kilowatt hours of electricity consumed by the three legs of power distributed throughout Building 18. Mr. Cunkelman and Mr. Cooper further assisted analysis with building floor plans, advice on where to look for needless energy consumption and provided heating and chilled water flow rates over multiple month periods. The 15 minute average utility consumption was compared to the total energy consumption from the MIT fiscal year 2005 internal audit which details the chilled water, steam and electrical consumption per building.

2.2 Building Overview

Building 18, also known as the Camille Edouard Dreyfus Building was originally opened for occupancy on December 15th 1969. The building was originally designed for chemistry laboratories by I.M. Pei and associates and has functioned as such since. Building 18 underwent a major renovation which was finished in 2003 modernizing the chemistry labs. The renovation opened up the floor plan, increased the number of fume hoods in each lab, and increased the hood density beyond any other building on campus. All fume hoods in the building were replaced with a modern vertical and horizontal sash design which was intended to mitigate the intense airflow required by such a high hood density.

The normal operation of each fume hood's sash uses four horizontally sliding glass barriers of equal size. The four glass barriers slide on two parallel horizontal tracks with two units of glass per track. The maximum opening during horizontal operation of the fume hood is two times the width of a glass barrier and in this configuration the glass barriers overlap completely. Each glass barrier is approximately 16 inches wide; this allows the operator of the hood to reach around the glass barrier with both hands and manipulate the experiment with a shield of glass protecting their face and torso while minimizing airflow through the hood. In practice this efficient operation of the hood is not utilized. For the purpose of easy experiment set-up and break-down, the glass barrier and track assembly slides vertically opening an area equal to four times the standard glass barrier. Faith in the effectiveness of the modern sash design caused the renovation architects, Goody Clancy, to omit an exhaust heat recovery system in the renovation.

Building 18 has five floors above ground and two levels below ground. The five upper floors feature chemistry laboratories and offices. The first through fourth floor each have seven laboratories, while the fifth only has five labs. The sub-basement features seven chemistry laboratories with higher security than those above ground and the hallway windows are obstructed. The sub-sub-basement houses the mechanical room and the laser laboratory. There are three main air handlers which provide conditioned air to the laboratories and offices. These air handlers are driven by fans totaling one-thousand horsepower and pumps totaling three-hundred-and-forty horsepower.

2.3 Electrical Energy Balance

Building 18 consumes 7.2 million KWH of electricity, 2.7 million Ton-Hours of chilled water, and 35.9 million pounds of steam yearly. Building 18 consumes a great deal of electrical energy therefore an electrical energy balance was sought first. In a normal office building, the lighting load accounts for approximately 20% of the total electrical load per year. Accordingly the initial light meter readings identified Building 18 as a light polluter - excessively well lit regardless of necessity, economy, or need but as an architectural statement piece opulently lit during all hours of the day and night.

3:00 PM (lights are on)

6:00 PM (lights on)

4:00 AM (lights on)

6:30 AM (lights on)

12:00 PM (lights are on)

Figures 3-8: Time Lapse Photography of Building 18

All of the light fixtures in the building were tallied and assigned a load value for their particular type of ballast and bulb configuration, yet the lighting load only accounts for approximately 5 percent of the building's yearly electrical load. Since the somewhat excessive lighting of Building 18 only accounted for 5 percent of the total load it was clear that there are some massive electrically powered systems at work below the surface.

The Andover Controls (TAC) software determined the steady state operation of the supply and exhaust fans as a percentage of the maximum fan speed. By relating the steady state fan speed to the design horsepower, the yearly electrical load due to fan operation was approximated. A fan's electrical load relates to the cube of its maximum speed percentage. Design horsepower was sourced from the building's mechanical drawings, and the value *0.7457* converts horsepower to KW.

$$\text{Power consumed by fans (KW)} = 0.7457 * \text{design HP} * (\text{fan speed \%})^3$$

Equation 2: Fan Speed to Power Consumption Conversion

As tabulated in Appendix C, the load approximation due to the fans is equal to 3.3 million kilowatt hours, or 45 percent of the 7.2 million kilowatt hours of electricity consumed by the building in fiscal year 2005. The approximation was developed using equation 2: the continuous power consumption for each fan was determined and then extrapolated for a year's duration. The electrical power supplied to Building 18 is divided into three legs: A, B, and Emergency. The internal audit for fiscal year 2005 provided the monthly meter readings for each leg. The General Electric meters for each supply leg are not interfaced with MIT's Pi utility-logging application and are manually monitored. The Pi system monitors the steam, chilled water, and total electrical output of the Co-Gen plant but does not currently have the sensor infrastructure to monitor each building individually.

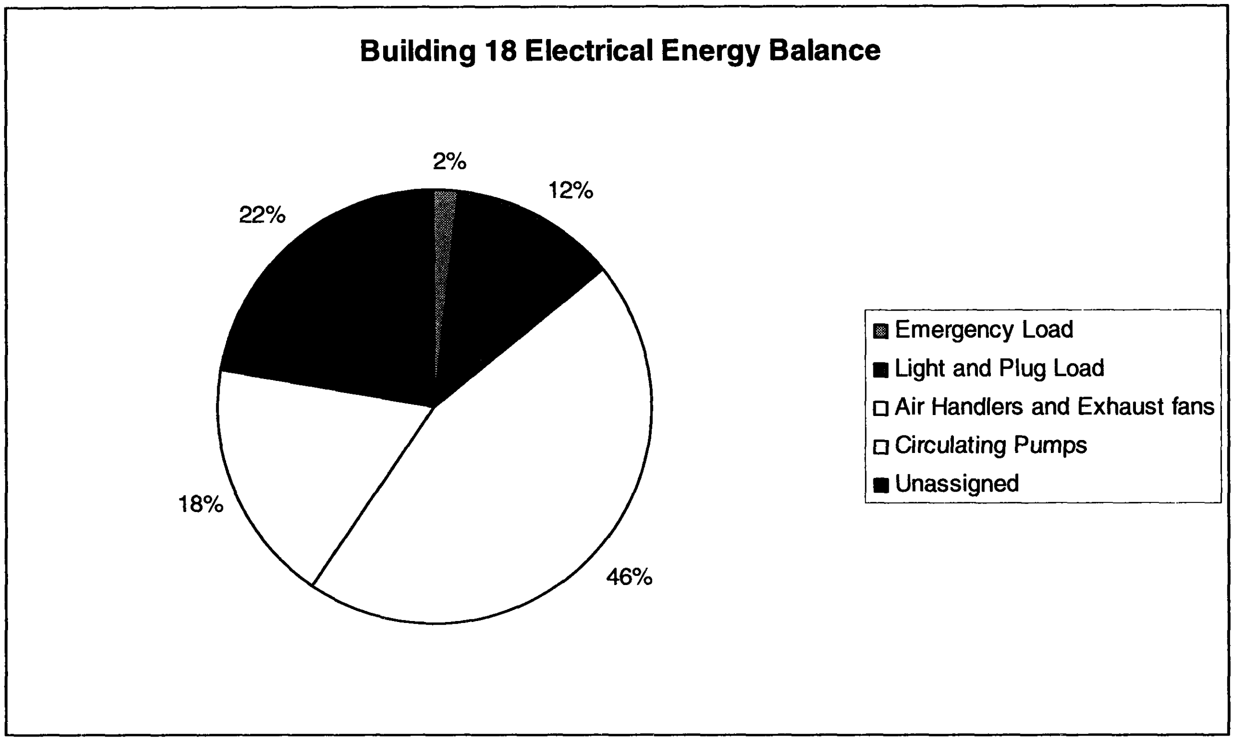


Figure 9: Electrical Energy Allocation for Building 18

The A-leg supplies 120V and 240V which powers the light and plug load for the building. This load totaled 886,125 kilowatt-hours for fiscal year 2005, or 12.2 percent of the total load. Accordingly the plug load accounts for 7 percent of the yearly draw. The emergency leg only accounted for 2 percent of the yearly load. The total known load increased to 59 percent: clearly missing a large portion of some major system at work in the mechanics of Building 18.

The mechanical room was examined in more detail and it was immediately obvious that there was the entire system of water pumps drawing from the supply of leg B which provides 480V and 240V power for the mechanical systems: leg B accounts for 85 percent of the building's total consumption since it also drives the supply and exhaust fans. Each pump in the mechanical room was cataloged noting the pumps power rating and state (on or off). Floor 00 (the sub-sub-basement) also has a secondary mechanical room with a chiller driven by two 37 kilowatt motors and associated booster pumps – those pumps and motors were also include in this analysis. Using only the pumps which were running in the calculations, another 18.4 percent of the yearly electrical draw was allocated bringing the total assigned load to 78 percent. The remaining 22 percent is attributed to pumps outside the mechanical room, smaller exhaust fans, and an unknown amount of energy consumed in the laser lab off leg-B. It is reasonable to regard this data as a thorough electrical energy balance of Building 18.

2.4 Heating and Cooling Assessment

Building 18 is conditioned using steam and chilled water from MIT's Co-Gen plant. The air handlers provide supply air at the temperature of 55 degrees Fahrenheit to the laboratories and offices after removing excess humidity if necessitated by exterior conditions. To maintain the correct temperature in each lab, the supply air is heated or cooled by a secondary coil in a variable-airflow-velocity box (VAV) in close proximity to the laboratory. The heating and cooling system of Building 18, because of the high density of fume hoods, must supply a great deal of conditioned air to maintain a comfortable work environment in the laboratories: the supply flow must equal the large exhaust flow. The density of fume hoods results in an extremely large flow of conditioned air out of the building. During the heating and cooling season conditioned air possesses potential energy relative to the environment. The air exhausted from Building 18, though contaminated, possesses reusable energy, but the building is not equipped with an exhaust heat recovery system, so that potential energy is lost.

The absence of the exhaust energy recovery system is not the sole problem with Building 18, since the hoods used throughout the building are designed to minimize excess exhaust airflow. The problem is inefficient human interaction with an otherwise well designed product, therefore the absence of a heat recovery system magnifies the problem. By examining both the behavioral and mechanical aspects of the fume hood's operation an approximate figure of potential energy savings in the form of lower steam, chilled water, and electrical consumption will be determined.

2.5 Fume Hood Design and Operation

The fume hoods used throughout Building 18 feature a dual sash arrangement which move vertically to fully remove obstruction during set-up and break-down of experiments and horizontally for normal interaction with volatile and noxious chemicals in the protected hood environment. Because of the difficulty in observing the single floor of laboratories below ground (floor 0) due to obstructed view, only the five floors of labs above ground presented a reliable research opportunity to determine the nature of the day to day exhaust hood operation.

Figure 10: 18-206 at 2:00am (4 hoods open)

The fume hoods are designed to provide a continuously high face velocity at the opening of the sash to prevent harmful gas or vapors from escaping into the greater laboratory environment. The flow rate is monitored by the Andover Controls system which correlates that to the sash position of the hood, also monitored in real time. Each hood is equipped with a venturi valve a few feet downstream in the exhaust duct. The Phoenix controls venturi valve is a solenoid operated butterfly type resistive flow device which modulates the airflow rate through each hood to maintain a consistently high face velocity. The minimum flow from each hood is 300 CFM and the maximum flow is 850 CFM. When the fume hood sash is open, the control system must increase the air flow rate through that hood to keep the face velocity at or above the required minimum. The operation of these exhaust hoods indicate a behavioral problem due to carelessness or naiveté.

Figure 11: 18-544 at 11:00pm (3 hoods open)

Chapter 3: Fume Hood Behavior

3.1 Day and Night Observations

The fume hoods in building 18 were observed over the period beginning in November of 2005 and ending in April of 2006. The position and the actual use of the hoods was observed at varying hours of the day and night to assess how the scientists interact with the fume hoods and if the large conditioned airflow through the hoods is necessary for operation of the research and teaching laboratories housed in Building 18. The following charts indicate the total number of hoods open for the upper five floors of Building 18. There are 156 hoods in those upper five floors. During the night observations there were, at most, 10 people working in the laboratories on the upper five floors. During the daytime there were more people working in the labs, necessitating the hoods being open, yet there were many more hoods open than people to interact with the experiment or lack there-of inside of the fume hood.

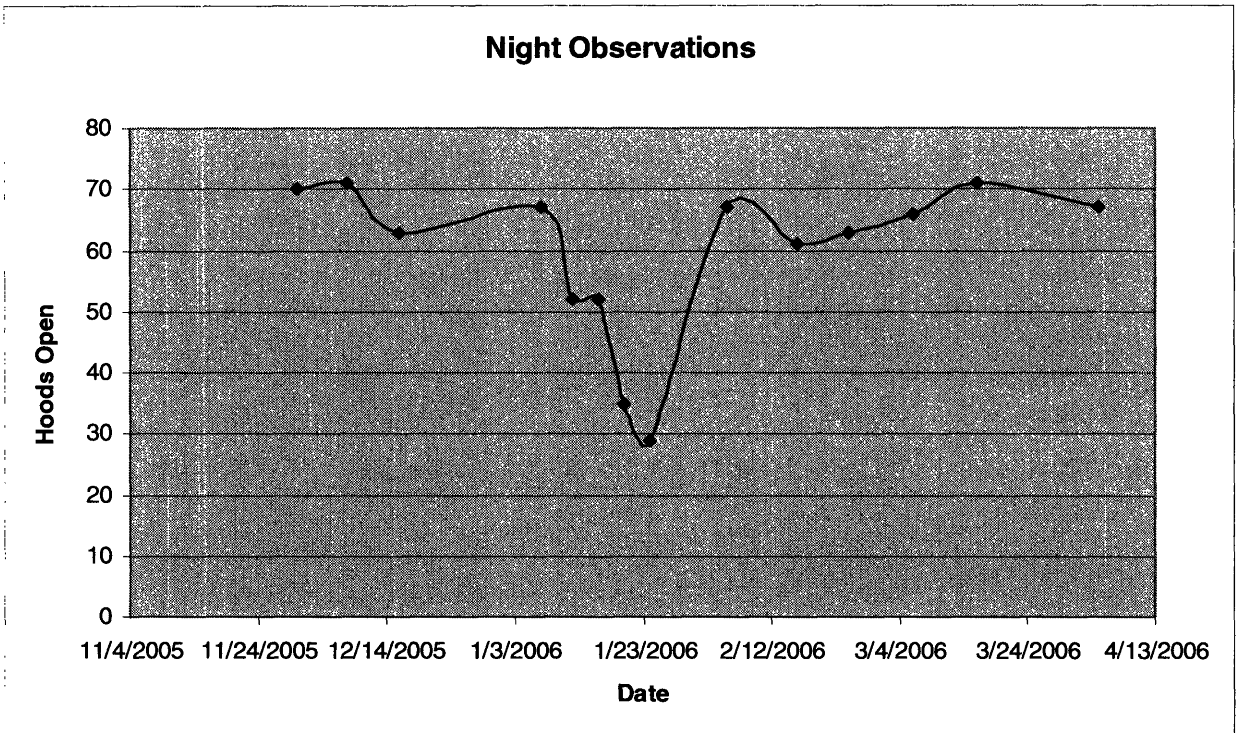


Figure 12: Nighttime Fume Hood Observations

There is a large dip in the total number of hoods open around January 23rd 2006. This date coincides with the end of the Independent Activities Period. Classes taught during January ended at that point in time, and habitation of the labs would transfer to different students using the space during the regular semester.

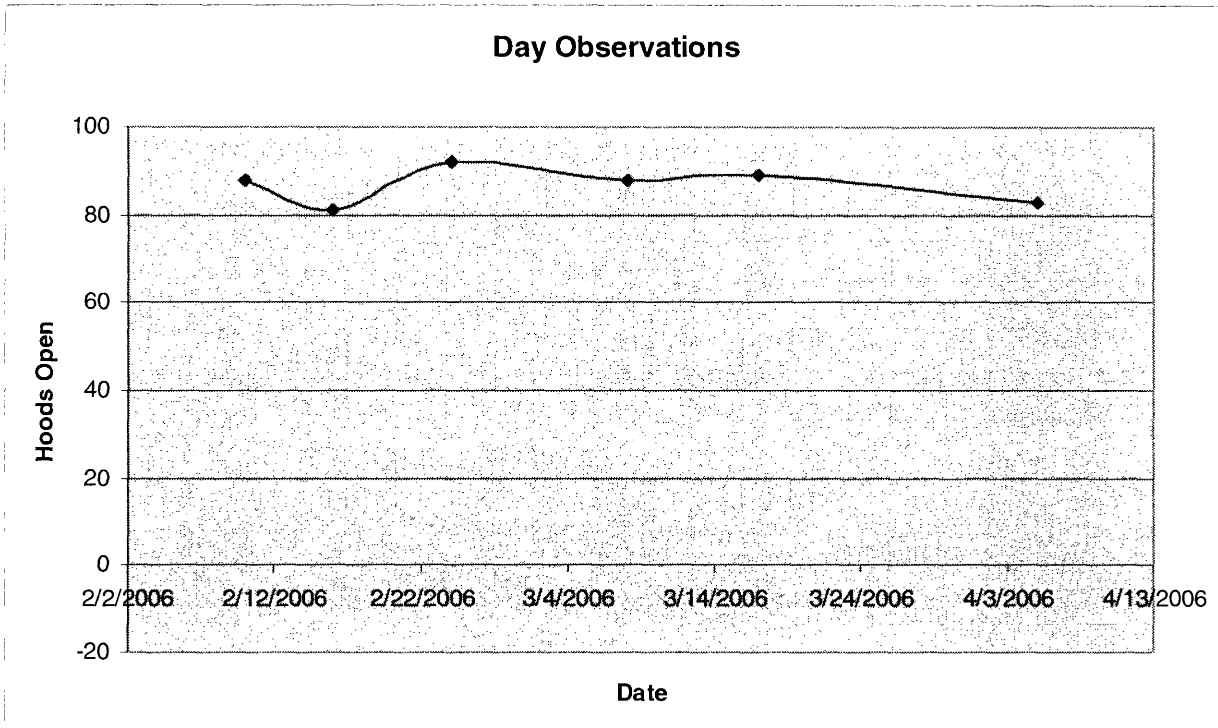


Figure 13: Daytime Fume Hood Observations

As the two charts indicate, there is a large portion of fume hoods open at all hours of the day and night. The majority of these hoods are open needlessly. More alarming than the sheer quantity of hoods open is the relatively small change in fume hoods open from day to night as evidenced by the following chart. The people who use the labs do not close hoods which are not in use while they are working in the labs. They do not close the hoods when they leave for the day. Furthermore there is one laboratory on the first floor where a computer workstation is installed inside of the fume hood – this particular hood has been consistently open in the vertical orientation during the six month period of observations. Again the vertical opening of the fume hood sash produces the maximum airflow through the hood and is only supposed to be used in this configuration during set-up and break-down of experiments.

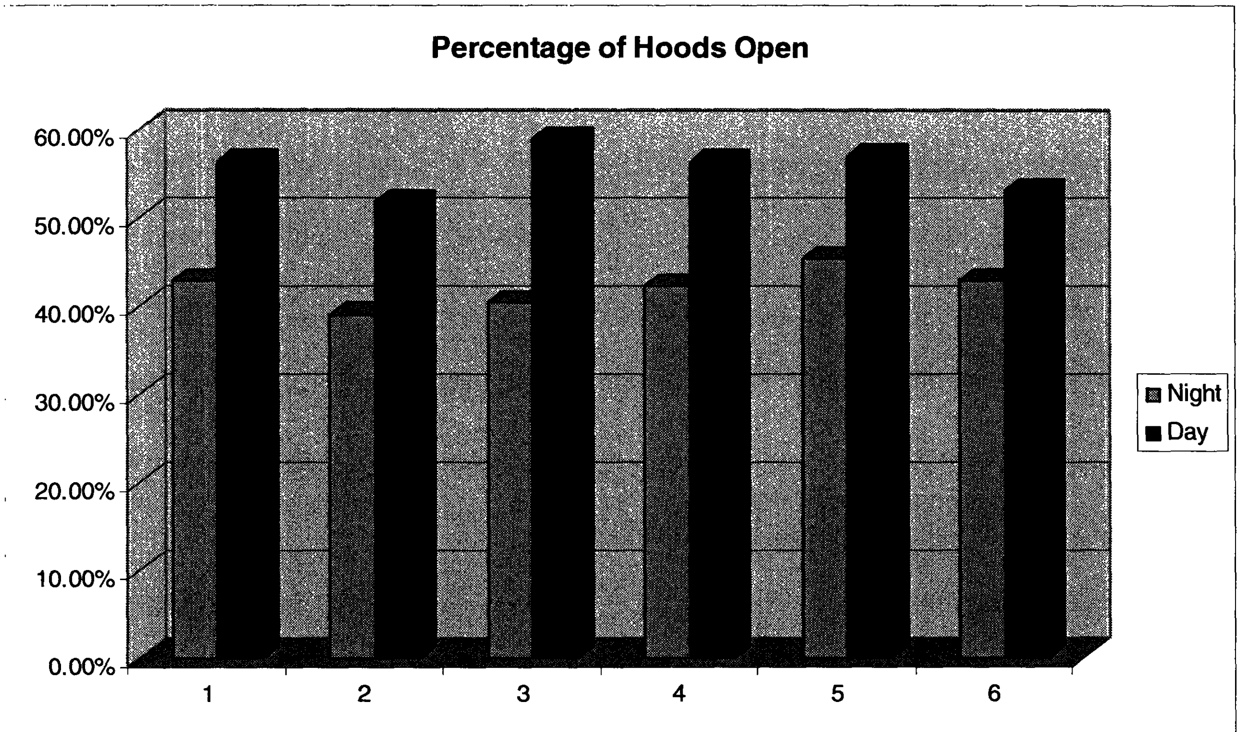


Figure 14: Percentage of Hoods Open Day and Night

Instances of particularly irresponsible behavior include the unnecessary removal of the horizontally sliding sashes and the debilitation of the excess flow alarm. The fume hoods in Building 18 are designed such that the hood can be fully open to ease set-up and break-down, but on a few occasions the hoods were partially dismantled – one of the four sliding glass sashes was removed. Removing one of the horizontally sliding sashes gives the Andover Controls software a false reading resulting in dangerously low airflow and an insufficient face velocity. Attached to each hood there is an airflow meter which is programmed with an alarm set-point if the hood is consuming too much energy. Some of these flow-meter-alarms have been disabled by jamming the mute button with scraps of paper.

3.2 Potential Energy and Monetary Savings

Reducing the amount of open hoods in Building 18 will have an immediate impact on the amount of electricity, steam, and chilled water consumed yearly. On average, during the night time observations, there were 67 fume hoods open on the upper five floors of the building. The night observations were between the hours of 9:00 pm and 9:00am and at most there were 10 people using the fume hoods on the early end of the spectrum (10pm), but on average there were fewer than five people in Building 18 using the hoods.

An approximation of the continuous airflow through Building 18 was determined. This approximation considered the office space and hallways in accordance with the ASHRAE standards and combined that with the known flow through the labs. Reducing Building 18's total airflow conserves electrical energy regardless of season by decreasing the constant fan load on supply leg B. When fully closed each fume hood flows 300 CFM and when fully open the hoods flow 850 CFM. The total minimum airflow through the 156 exhaust hoods is 46,800 CFM.

*Minimum Exhaust hood flow (all closed) = Number of hoods*Minimum flow*

Equation 3: Minimum Hood Flow

If we reduce the amount of nighttime open hoods from 67 to 0, Building 18's exhaust flow rate would decrease by 46,300 CFM. It is reasonable to approximate a reduction from 67 hoods open throughout the night to 0 if the hoods in use during the night are used efficiently as the flexible sash design is intended.

*Night Time Flow Reduction = difference in hoods open * (Max Flow – Min Flow)*

Equation 4: Impact on Total Flow by Closing Hoods

Each lab is also equipped with a general exhaust which flows 1350 CFM for a total flow of 44,550 CFM of general exhaust for the building. The current nighttime exhaust flow out of Building 18 is 128,200 CFM. The office and hallway flow was estimated in conjunction with the 2001 ASHRAE ventilation rate standards which the renovation of the building was designed around.

$$\textit{Current Flow rate} = \textit{Min Hood Flow} + \textit{General Exhaust Flow} + \textit{n observed open hoods} * (\textit{Max flow} - \textit{Min Flow}) + \textit{Office and Hallway flow}$$

Equation 5: Current Total Building Exhaust Flow

Assuming that a reduction in exhaust flow would necessitate an equal reduction in supply airflow, and, accordingly, would reduce fan speed, a potential electrical savings of 1.0 million KWH per year would result.

$$NewFanSpeed = SteadyStateFanSpeed * \frac{CurrentFlowRate - PotentialFlowSavings}{CurrentFlowRate}$$

Equation 6: Reduced Fan Speed Due to Closed Hoods

$$NewFanEnergy = (NewFanSpeed\%)^3 * DesignHP$$

Equation 7: Reduced Fan Energy Consumption

The night time conservation effort from 9pm to 9am could decrease the total electrical consumption of Building 18 by 8.5 percent. Research indicated that approximately 40 of the 88 open hoods during daytime operation of Building 18 were not in current use. Applying the same logic and equations to the daytime conditions, a 6.5 percent reduction in yearly electrical load would result. The day and night savings would decrease Building 18's electrical bill by $123,000 per year.

	FY 2005	FY 2006 (projected)	cost per
Chilled Water	\$0.23	\$0.23	Ton-hours
Electricity	\$0.115	\$0.122	Kilowatt-hours
Steam	\$14.30	\$17.50	1000 pounds

Table 4: MIT Utilities Pricing

The cost of fuel oil, natural gas, and purchased electricity is increasing rapidly. MIT will not realize a significant increase in the cost of purchased electricity until the end of summer 2006 because the Institute pre-purchased electricity with N-Star on contract through July. It is both fiscally and environmentally responsible to reduce the consumption of energy. The fiscal year 2005 report indicates that Building 18 consumed \$1.9 million in utilities (electricity, steam, and chilled water). In comparison, Building 39, the number one energy consumer per square foot, generated a utility bill of \$2.2 million and the third highest energy consumer per square foot, the Steely G. Mudd building (E17), consumed \$1.1 million in basic utilities.

The amount of steam and chilled water consumed by Building 18 could be significantly reduced with responsible fume hood operation. The Degree Day approximation was used to determine the potential energy savings during the heating and cooling months. Due to the high rate of ventilation in Building 18 the balance point temperature was chosen to be 60 degrees instead of the traditional 55 degree temperature. The bin data for Boston Massachusetts indicates 4700 heating degree (^{o}C) days and 1700 cooling degree days during fiscal year 2005. Boston and Cambridge Massachusetts experience identical environmental conditions for the purpose of this approximation.

$$Q = \dot{m} * cp_{air} * HeatingDegreeDays$$

Equation 8: Heating Degree Day Energy Approximation

The $\dot{m}$ term is the preventable daily flow rate through the exhaust hoods *i.e.* the flow through the 67 needlessly open fume hoods at night and the 48 unused open hoods during the day. There are 32 fume hoods in the sub-basement level of Building 18 which were impossible to regularly observe. The ratios of open to closed hoods for the upper five floors during day and night were applied to the 32 hoods in the sub basement (i.e. *67/156* night and *88/156* day). The preventable flow during nighttime operation of Building 18 exhausts 3,600 MBTU of conditioned air. The daytime operation exhausts 2,200 MBTU of conditioned air. If this energy was conserved, assuming a 0.75 efficiency in the initial heat transfer from steam to air, the yearly steam consumption of Building 18 would drop by 17 percent. This percentage drop does not include the reduction in steam use during the cooling months which dehumidifies the supply air. The energy savings during the heating months would decrease Building 18's steam bill by $106,000.

The latent and sensible cooling loads for Boston per CFM were referenced from the ASHRAE journal. The latent load was determined by the relationship cited below.

$$LatentLoad(BTU) = \frac{(OutsideHumidityRatio - 65gr/lb) * \dot{m} * h_{fg}}{Grains/lb}$$

Equation 9: Latent Load

In this equation $\dot{m}$ represents pounds-per-hour of one CFM and h_{fg} is the heat of vaporization of water at standard temperature. The reduction of 65 grains of water per pound of air reflects a comfortable proportional decrease in humidity from outside to inside. The latent load was determined to be equivalent to 2.0 ton-hours per CFM of ventilation. The sensible load was determined by the cooling degree day approximation which follows the same format as the heating degree day energy calculation.

$$Q_{sensible} = \dot{m} * cp_{air} * CoolingDegreeDays$$

Equation 10: Cooling Degree Day Energy

The total potential savings for the cooling months was then computed using the following equation.

$$CoolingLoss = Q_{sensible} + nOpenHoods * \frac{550CFM}{hood} * LatentLoad$$

Equation 11: Total Preventable Cooling Losses

The total savings potential if unused hoods were kept closed for the cooling months equals a 6,600 MBTU per year savings. The decrease in cooling load would reduce Building 18's chilled water consumption of 20 percent per year if one assumes a heat exchanger efficiency of 0.75. This reduction in consumption equates to a savings of $127,000 per year in chilled water.

One might wonder how the consumption of energy by a single fume hood relates to a more tactile energy standard than British Thermal Units. The average single family home in the north eastern United States consumes 115 million BTU per year for heating and cooling. The exhaust flow through a single fume hood over a year consumes 127 million BTUs: more energy than an average single family home consumes in the same time period. This single hood exhaust flow costs MIT $1000 per year in steam and $1200 per year in chilled water.

What would be the impact of an exhaust heat recovery system for Building 18? Assuming a heat exchanger efficiency of 0.75, one then calculates the total mass flow rate through all fume hoods and applies the degree day approximation for total energy consumed during the heating season.

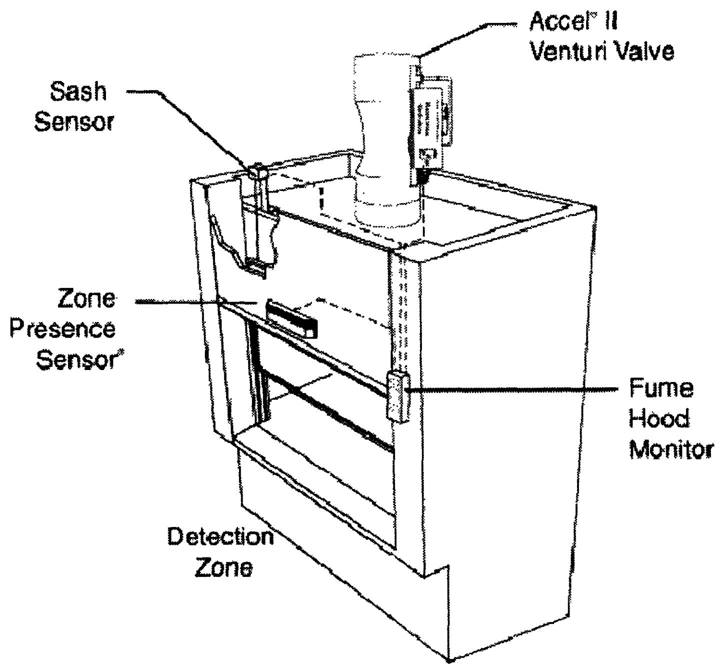
$$Q_{HeatRecovery} = 0.75 * \dot{m}_{total} * cp_{air} * HeatingDegreeDays$$

Equation 12: Energy Savings from an Exhaust Heat Recovery System

An exhaust heat recovery system could salvage 9,900 MBTU per year. This is equivalent to 22 percent of Building 18's total steam consumption or $138,000 per year in steam.

3.3 Methods for Behavioral Change

The most promising method to change the way people interact with fume hoods in their research and learning activities is through education of the actual impact these hoods have on the environment; and the potential energy savings closing one of these hoods could have. A website is being developed showcasing the information assembled in this thesis and will be permanently hosted by MIT's Energy Classes site. The web page will be linked to MIT's Walk the Talk initiative, the MIT Energy Club, and hopefully other websites with similar interest. The best way to reduce the amount of hoods open, though, is to directly interact with the people who use them. Signs will be developed and attached to each fume hood indicating the energy wasted through needless airflow through a single hood over the year could single handedly heat and cool a single family house for the same time period.



Usage Based Controls system. The system determines usage by sensing the presence of a person in a well-defined detection zone in front of the hood. When no one is present, the system sets the airflow face velocity to a safe "standby" level—typically 60 fpm. When the operator enters the detection zone, the system instantaneously (within one second) increases the face velocity to a higher level—typically 100 fpm.

Figure 15: Phoenix Controls Usage Based Control System

Phoenix Controls, manufacturer of the current fume hood and control valves, has developed a remedial solution to the problem of careless use of fume hoods. They have developed a motion sensor which attaches to the hood sash and interfaces with the control software which also monitors the sash position. The usage sensor, when no presence is detected, reduces the face velocity of the fume hood to 60 feet per minute (a 40% reduction) and can further decrease airflow if the sashes are fully closed and not in use (up to 80%). If the Phoenix Usage Based System satisfies safety standards, it could significantly decrease energy consumption in Building 18.

Chapter 4: Conclusion

The growing production of greenhouse gas threatens to change our environment with potential consequences both threatening and unknown. The production of GHG due to transportation is a factor of 10 less than that of MIT's utilities – the MIT community needs to break from the petroleum-centered view of the world. The large potential for energy conservation by implementing a small behavioral change, such as keeping fume hoods closed when not in use, implies that other such opportunities for energy conservation exist on campus. The total savings from efficient use of Building 18's fume hoods can save the Institute approximately $350,000 per year while reducing greenhouse gas emissions. The cost of this conservation effort is minimal.

Building 18 is evidence that environmentally conscious engineering and design is absolutely necessary and must be integrated into all aspect of building and infrastructure planning. Unlike automobiles and transportation devices, buildings have a long useful life in the range of 50 to 100 years. Oversights in construction and design (like the absence of a heat recovery system in Building 18) will impede our efforts to reduce the emissions of GHG and conserve energy. In the case of Building 18, this thesis has demonstrated that utility consumption can be decreased by 17 percent by using out facilities efficiently and responsibly. Other potential optimizations in energy consumption must exist throughout the MIT infrastructure. Better technology and more efficient production and consumption of energy is doomed to deteriorate the earth if we do not change our myopic attitude towards our planet and energy use.

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APPENDIX A: STEAM AND CHILLED WATER CONSUMPTION

The following charts track the steam and chilled water consumption of Building 18 and compare that consumption to outside temperature. These trends were used to determine the steady-state consumption of chilled water not attributed to seasonal demands, and to confirm the Institute's internal energy consumption audits for fiscal years 2005.

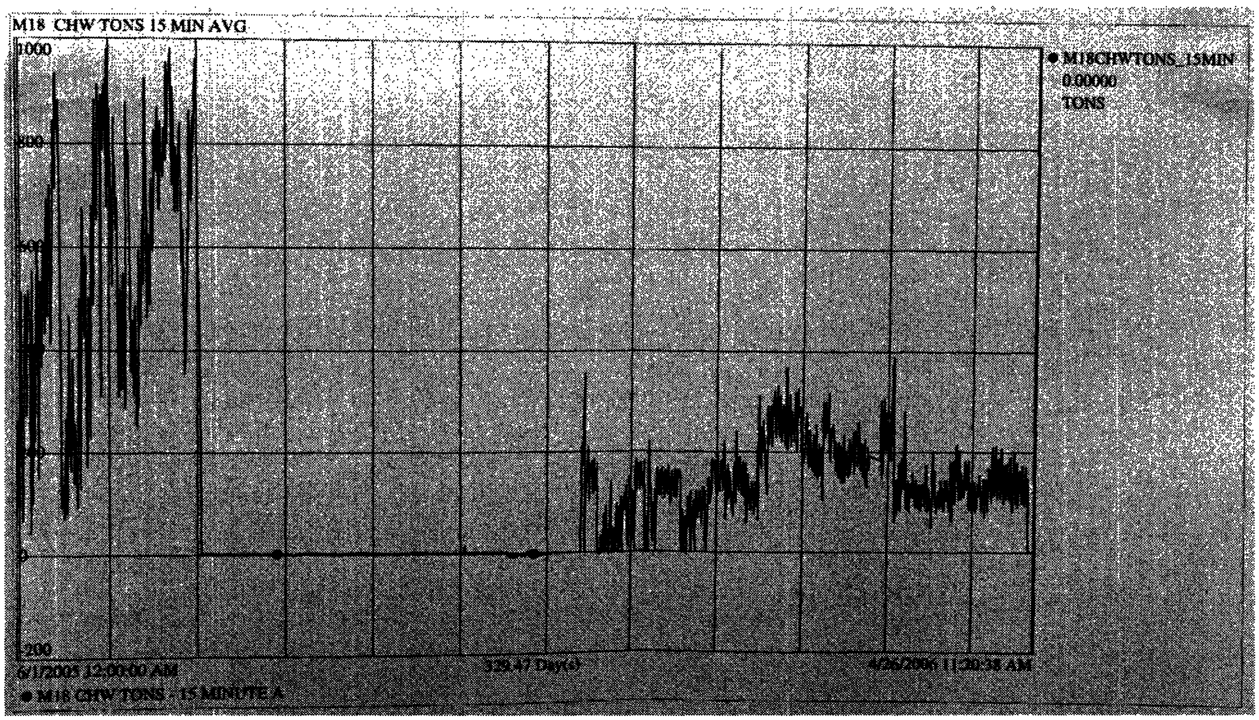

Figure 16: Chilled Water Consumption over 329 days

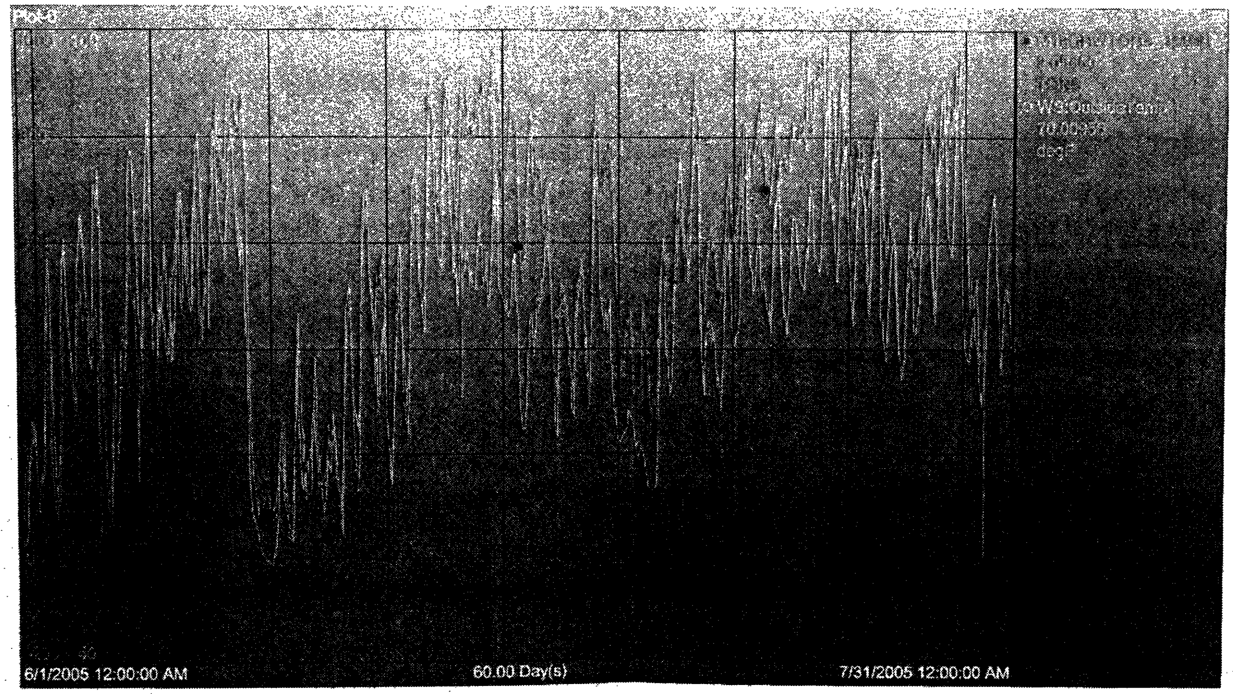

Figure 17: Chilled Water and Outside Temperature from 6/1 to 7/31/2005

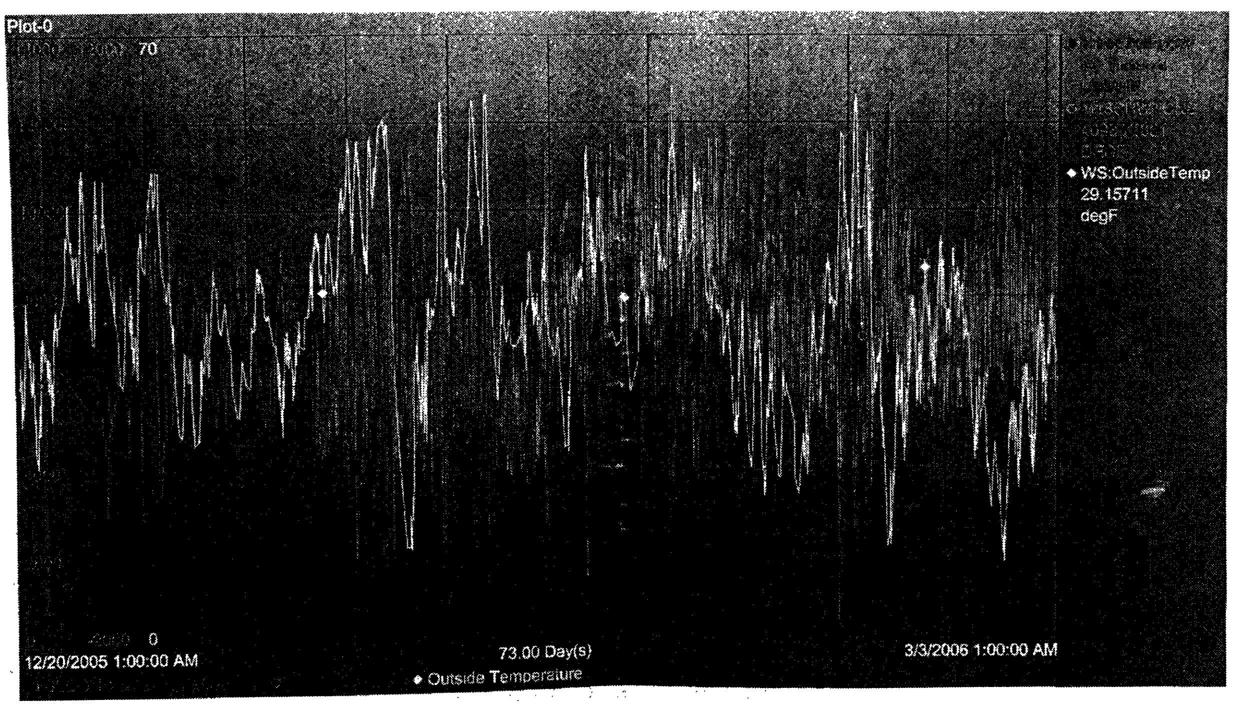

Figure 18: Chilled Water, Steam, and Outside Temperature from 12/20/2005 to 3/3/2006

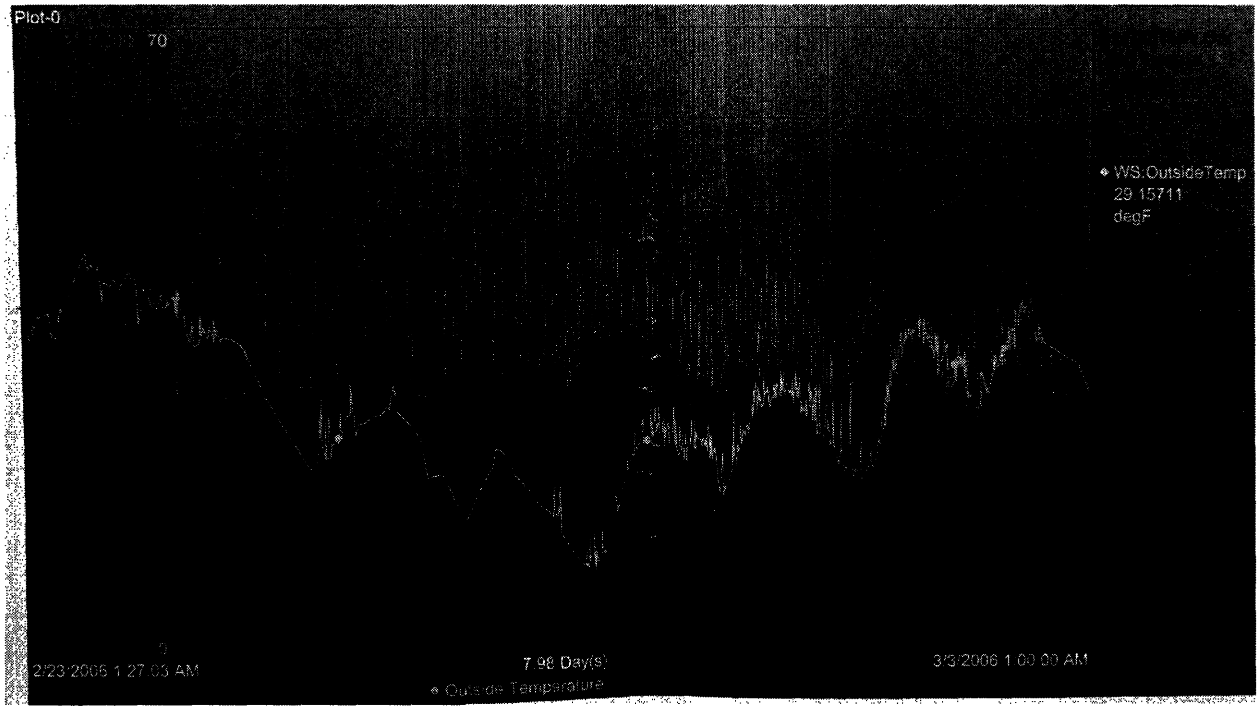

Figure 19: Chilled Water, Steam, and Outside Temperature from 2/32 to 3/3/2006

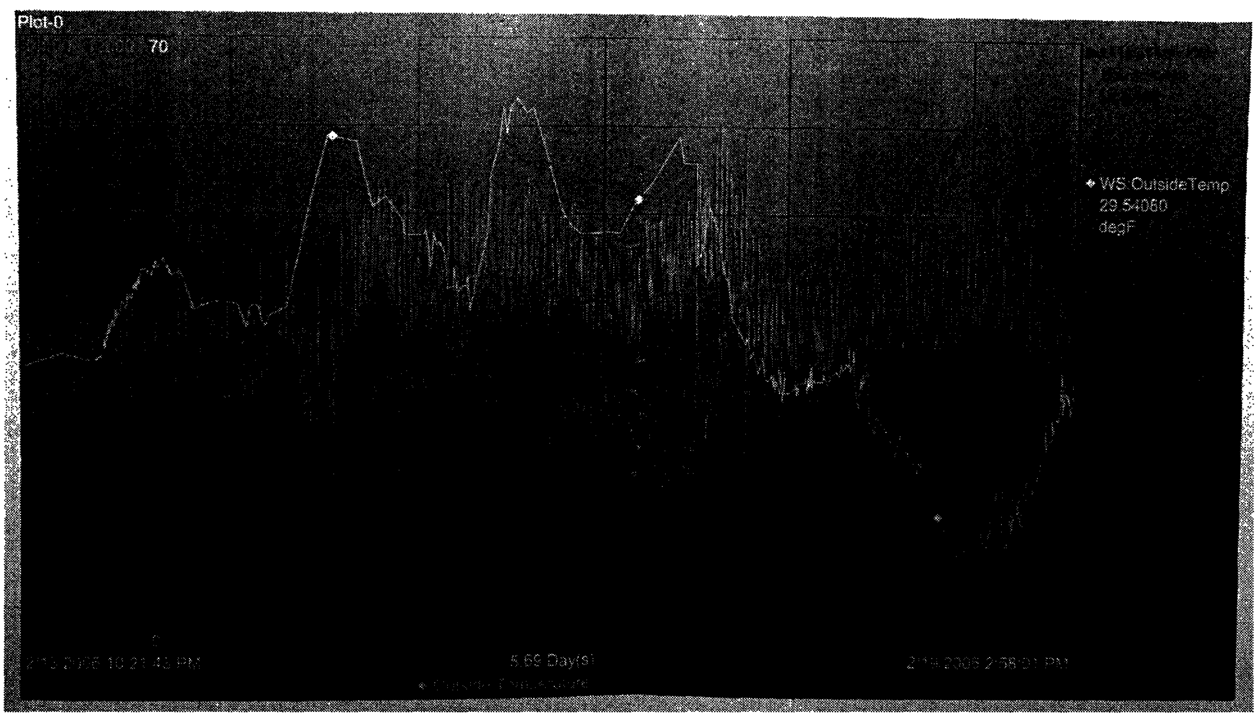

Figure 20: Chilled Water, Steam, and Outside Temperature from 2/13 to 2/19/2006

APPENDIX B: FUME HOOD OBSERVATIONS

ROOM	11/30/2005	12/8/2005	12/16/2005	1/7/2006	1/12/2006	1/16/2006	1/20/2006	1/24/2006	2/5/2006	2/16/2006	2/24/2006	3/6/2006	3/16/2006	4/4/2006
	18:00	3:00	1:00	23:00	22:30	0:03	2:00	2:00	23:45	2:15	3:00	1:00	0:15	22:00
523	2	2	2	0	2	2	1	1	3	2	3	1	3	1
525	0	1	1	2	1	2	0	0	2	2	1	2	2	1
543	4	2	3	4	2	3	3	2	2	1	2	3	2	3
544	3	1	0	2	3	3	2	1	3	3	1	2	4	4
563	2	5	4	2	2	1	0	0	4	3	2	4	4	4
405	0	2	2	0	0	1	2	2	2	2	1	3	0	0*
406	0	3	2	1	2	1	0	0	2	3	3	3	2	0*
423	0	2	1	0	1	2	0	1	2	2	3	2	1	3
425	2	2	1	2	2	0	0	1	1	1	2	1	2	1
443	2	2	0	1	0	1	2	0	1	2	1	2	1	1
444	2	1	3	3	1	1	2	3	3	3	3	2	4	0
463	1	3	2	2	1	0	1	0	2	0	1	3	2	1
305	3	2	2	3	3	4	3	2	4	3	2	2	3	3
306	2	4	0	0	3	2	1	2	3	2	1	3	2	2
323	5	2	3	3	2	3	0	0	0	4	0	4	3	3
325	5	1	2	4	1	0	3	0	1	2	2	3	2	4
343	3	5	2	3	2	2	1	1	2	0	0	0	4	2
344	1	2	1	2	1	2	2	1	1	1	4	3	4	1
363	1	1	1	0	2	3	0	0	3	2	2	1	3	2
205	0	1	3	1	1	2	2	0	2	3	3	1	2	2
206	4	3	1	3	3	3	3	2	2	1	2	3	4	3
223	3	2	2	4	2	2	0	0	1	2	4	2	2	3
225	5	4	1	2	3	3	2	0	3	4	1	1	1	5
243	5	3	4	4	2	1	1	2	2	2	2	3	0	3
244	3	2	2	3	0	0	0	0	3	0	4	0	3	0
263	1	1	2	2	1	0	1	1	2	2	2	1	2	0
105	0	2	2	2	1	2	0	2	1	3	3	3	1	2
106	0	1	1	0	2	1	0	2	2	1	2	2	2	1
123	3	4	3	1	0	1	1	1	0	2	0	2	1	5
125	3	1	2	4	1	1	0	0	1	1	2	1	2	1
143	1	1	2	2	2	1	2	0	4	0	2	2	0	2
144	2	2	2	2	3	1	0	1	2	1	1	0	2	0
163	2	1	4	3	0	1	0	1	1	1	1	1	1	4
#	70	71	63	67	52	52	35	29	67	61	63	66	71	67
%	45%	46%	40%	43%	33%	33%	22%	19%	43%	39%	40%	42%	46%	43%

Table 5: Night Fume Hood Observations

The numbers in each column represent the number of observed open hoods for that date and time. The room numbers have been truncated to fit on one page for convenient viewing. All observations were in Building 18, so room 144 is actually 18-144.

ROOM	2/10/2006	2/16/2006	2/24/2006	3/8/2006	3/17/2006	4/5/2006
	14:00	11:00	15:00	13:00	10:00	13:00
523	4	3	3	4	0	4
525	3	2	2	3	2	0
543	3	4	5	2	4	3
544	2	3	3	2	1	2
563	4	5	2	4	5	5
405	1	1	2	1	1	1
406	3	4	3	0	3	0*
423	4	4	4	1	0	2
425	2	1	2	2	2	2
443	1	0	1	2	2	2
444	3	3	4	4	3	1
463	4	3	1	4	4	3
305	2	4	3	4	2	1
306	3	2	3	2	4	3
323	5	3	4	5	2	3
325	4	3	4	4	3	4
343	5	4	3	3	4	3
344	2	3	3	5	4	4
363	1	3	2	3	2	4
205	4	2	0	3	5	2
206	3	3	4	4	3	4
223	3	4	2	3	4	4
225	3	2	4	2	3	4
243	1	3	3	4	5	4
244	4	2	4	1	1	1
263	2	3	4	0	0	0
105	3	2	3	2	0	1
106	2	1	2	2	3	1
123	1	0	4	1	3	5
125	2	2	3	4	5	3
143	3	1	2	3	3	2
144	1	1	2	3	4	3
163	0	0	1	1	2	2
#	88	81	92	88	89	83
%	56%	52%	59%	56%	57%	53%

Table 5: Daytime Fume Hood Observations

APPENDIX C: FAN AND CIRCULATING PUMP ENERGY DATA

Fan	Spec HP	Design HP	on/off	speed %	HP in Use	TAC Amp Reading	KW	new night speed	new day speed
EF-1	40	30.1	on	91	23	30.2	17	65	74
EF-2	40	30.1	off	0	0	0	0	0	0
EF-3	40	30.1	on	91	23	30.5	17	65	74
EF-4	40	33	off	0	0	0	0	0	0
EF-5	40	33	on	86.7	22	36.9	16	62	70
EF-6	40	33	on	87.3	22	35.4	16	62	71
EF-7	60	54	off	0	0	0	0	0	0
EF-8	60	54	on	97.6	50	78.3	37	69	79
EF-9	60	54	on	97.3	50	71.8	37	69	79
AH O-2	75	67	on	99.8	67	54.2	50	71	81
AH O-3	100	71.2	on	83.1	41	31.3	30	59	67
SF-1	125	109	on	89.9	79	54.3	59	64	73
SF-2	40	35	on	99.7	35	41.4	26	71	81
SF-3	15	12	on	95.9	11	14.3	8	68	78
SF-4	30	23	on	100	23	28.7	17	71	81
SF-5	125	101	on	83.3	58	44.9	44	59	68

Table 6: Supply and Exhaust Fan Power Data

Pump Description	ON / OFF	HP	Consumption
Baldor Super E	1	2	2.00
P-5 Paco Pump	1	5	5.00
P-6 Paco Pump	1	5	5.00
Domestic Water	1	5	5.00
Booster Pump	0	5	0.00
Bell + Gosstt	0	0.08	0.00
Bell + Gosstt	0	0.08	0.00
P-2	1	10	10.00
P-1	1	10	10.00
US Motors	1	1.5	1.50
731977 Condensate Return	0	10	0.00
731976 Condensate Return	0	10	0.00
Pump Heat Glycol P4	1	26	26.00
Pump Heat Glycol P3	1	26	26.00
Pump Heat HW P2	1	30	30.00
Pump Heat HW P1	0	30	0.00
Pump Heat HW P8	0	2	0.00
Pump Heat HW P7	1	2	2.00
Heating HW	1	2	2.00
Heating HW	1	2	2.00
Steam Condensate Return	0	0.5	0.00
Steam Condensate Return	0	0.5	0.00
AC 1	0	6	0.00
AC 2	1	6	6.00
FLUID SOLUTIONS FILTRATION SYSTEM			0.00
731985	1	5	5.00
731984	1	5	5.00
LABORATORY AIR COMPRESSOR			0.00
lab air compressor	0	15	0.00
CHILLED WATER PUMPS			0.00
#5	1	20	9.75
#6	0	20	0.00
Secondary Chiller Room			0.00
compressor pump 1	1	50.42	50.50
Compressor Pump 2	0	50.42	0.00
circulator pump	0	2	0.00
circulator pump	1	2	2.00
Totals (HP)		364.5	204.75

Table 7: Mechanical Room Circulating Pump Energy Tabulation

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