Developing a Low-Cost, Systematic Approach to Increase an Existing Data Center's Energy Efficiency

By

Jeremy M. Stewart

B.S. Materials Engineering, University of Cincinnati, 2003
M.S. Manufacturing Engineering, University of Washington, 2007

Submitted to the MIT Sloan School of Management and the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
AND
Master of Science in Engineering Systems

In conjunction with the Leaders for Global Operations Program at the
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Signature of Author ______________________
May 7, 2010
Department of Engineering Systems, MIT Sloan School of Management

Certified by ______________________
Leon Glicksman, Thesis Supervisor
Professor of Building Technology & Mechanical Engineering

Certified by ______________________
Sarah Slaughter, Thesis Supervisor
Senior Lecturer, MIT Sloan School of Management

Accepted by ______________________
Debbie Berechman
Executive Director of MBA Program, MIT Sloan School of Management

Accepted by ______________________
Nancy Leveson
Chair, Engineering Systems Division Education Committee
Professor of Aeronautics and Astronautics, Engineering Systems at MIT

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Abstract

Data centers consume approximately 1.5% of total US electricity and 0.8% of the total world electricity, and this percentage will increase with the integration of technology into daily lives. In typical data centers, valued added IT equipment such as memory, servers, and networking account for less than one half of the electricity consumed, while support equipment consumes the remaining electricity.

The purpose of this thesis is to present the results of developing, testing, and implementing a low-cost, systematic approach for increasing the energy efficiency of data centers. The pilot process was developed using industry best practices, and was piloted at a Raytheon site in Garland, TX. Because the approach is low-cost, there is an emphasis on increasing the energy efficiency of data centers' heat removal and lighting equipment.

The result of implementing the low-cost systematic approach, consisting of both technical and behavior modifications, was a 23% reduction in electricity consumption, leading to annual savings of over $53,000. The improvement to the heat removal equipment's energy efficiency was 54%. In addition to presenting the results of the pilot, recommendations for replicating the pilot's success are provided. Two major managerial techniques are described - creating an aligned incentive structure in both Facilities and IT departments during the data center design phase, and empowering employees to make improvements during the use phase. Finally, a recommended roll out plan, which included a structure for Data Center Energy Efficiency Rapid Results Teams, is provided.

Thesis Advisors:
Leon Glicksman, Professor of Building Technology & Mechanical Engineering
Sarah Slaughter, Senior Lecturer, MIT Sloan School of Management

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Second, I would like to thank the amazing team I worked with at Raytheon Intelligence & Information Systems – Roy Villanueva and Joe Hall – for their support during and after the internship that produced this thesis.

Third, I would like to thank my friends, colleagues and mentors at Boeing. I appreciate your advice, faith and sponsorship during the two year LGO program. I look forward to the making an impact and addressing the challenges that lie ahead.

Finally, and most importantly, I would like to thank my wife, my parents, and my in-laws for their love and support. I realize that the LGO program is one step in a lifelong journey, and I am glad that I have y'all by my side.

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1 Introduction

1.1 Project Motivation

1.1.1 Increase Energy Efficiency of Data Centers with Behavior Change

Energy efficiency in the US is lower than in all other developed countries, and a substantial amount of energy consumption could be avoided by changing energy consuming behaviors. The industrial sector accounts for nearly half of all the energy consumed, so it is ripe with opportunities for increased energy efficiency. One well-known area of potential improvement for almost all industries is data center efficiency. Because data centers are set-up and operated by information technology professionals, this project and thesis explores in depth the mechanisms for changing behavior of organizations containing such professionals. While much has been published on behavior change of individuals, few have explored what methods (i.e. incentives, organization alignment, and performance management) can be used to change the energy consuming behaviors of entire technical organizations. For example, how should organizations utilize awareness, commitment, action, feedback, and/or competition to maximize behavior change? Also, how should organizations develop and scale energy efficiency improvement processes? This thesis will explore both questions.

1.1.2 Use only Low-Cost Techniques to Change Behaviors

Energy consumption by data centers is costly and ironically, decreases the amount of upfront capital available to make infrastructure and equipment changes to existing data centers. Therefore, the goal of this project was not to develop a general improvement process for data centers; rather, the goal was to develop a <u>low-cost</u> improvement process for data centers that relied heavily on behavior change rather than capital investment for energy efficiency gains.

1.1.3 Reduce Emissions due to Energy Consumption

While energy reduction started as a cost reduction initiative, it is frequently becoming part of a larger corporate sustainability strategy.[1] Ideally, a corporate sustainability strategy would span a company's economic, environmental and social impacts, though in recent years there has been increased emphasis on an organization's environmental impact, most notably, their greenhouse gas (GHG) emissions.[2]

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[1] (Shah and Littlefield 2009)

[2] (EPA n.d.)

There are six major greenhouse gases being tracked by companies participating in GHG reduction programs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydroflourocarbons (HFCs), perflourocarbons (PFCs), and sulfur hexafluoride (SF_6).[3] The largest GHG emission from most manufacturing companies is carbon dioxide resulting from the combustion of fossil fuels.

1.2 Problem Statement

Raytheon Intelligence & Information Systems (IIS) was an ideal location to complete this thesis since most of their energy usage is due to data centers, and since the three motivations outlined previously apply to their business. First, IIS has an IT organization, comprised of technical professionals, responsible for both the initial design and the day-to-day operations of IIS data centers. Second, only $500 total was available to make technical upgrades; therefore, the improvement process developed had to be extremely low-cost and depend primarily on behavior changes to achieve energy savings. Third, IIS has aggressive GHG reduction goals, which are tracked and reported by the facilities organization.

Since the high-cost for electricity leads to a high overhead rate that lowers their likelihood of IIS winning cost-based defense contracts, there is an intrinsic reason for the IIS IT organization to strive to increase data centers' energy efficiency. Furthermore, because most of the electricity consumed by IIS is derived from fossil fuels, their energy consumption leads to additional GHG in the environment. This provides the Facilities organization incentive to help increase the energy efficiency of data centers. Since there are two organizations – IT and Facilities – who are incentivized to increase the energy efficiency of data centers, behavior change techniques were developed in such a way to apply to both organizations. Additionally, organization alignment, interaction, and incentives were considered levers to use to increase the teamwork necessary for large organizations to achieve energy efficiency reductions.

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[3] (EPA 2010)

1.3 Thesis Overview

The document is organized as described below:

Chapter 1 outlines the general motivation for the thesis and provides an overview of the thesis contents.

Chapter 0 provides the company background and a brief discussion of data centers and the

Chapter 3 presents the hypothesis for the study undertaken.

Chapter 4 describes existing knowledge on how to improve the energy efficiency of data centers, and outlines the developed pilot process that was used to test the hypothesis

Chapter 5 details the pilot data center and provides the before and after electricity consumption data.

Chapter 6 provides recommendations for improving the energy efficiency of data centers through engineering design and managerial technique, and through extensive roll-out of the piloted process with Rapid Results Teams.

Chapter 7 presents an overview of the business case, including a summary of key findings.

2 Background

2.1 Company Background - Raytheon

The Raytheon Company, established in 1922, is a technology leader specializing in defense, homeland security, and other government markets throughout the world. With a history spanning more than 80 years, Raytheon provides electronics, mission systems integration, and other capabilities in the areas of sensing, effects, communications and intelligence systems, as well as a broad range of mission support services. Raytheon has around 75,000 employees worldwide and generated $25 billion in 2009 sales.[4] Raytheon has the following six business units:[5]

Integrated Defense Systems (21% of sales and 29% of operating profits in 2008) is a leading provider of integrated joint battle space (e.g., space, air, surface, and subsurface) and homeland security solutions. Customers include the U.S. Missile Defense Agency (MDA), the U.S. Armed Forces, the Dept. of Homeland Security, as well as key international customers. Main product lines include sea power capability systems, focusing on the DDG-1000, the Navy's next-generation naval destroyer; national & theater security programs, including the X-band radars and missile defense systems; Patriot programs, principally the Patriot Air& Missile Defense System; global operations; and civil security and response programs.

Intelligence & Information Systems (13% of sales and 9% of profits) provides systems, subsystems, and software engineering services for national and tactical intelligence systems, as well as for homeland security and information technology (IT) solutions. Areas of concentration include signals and image processing, geospatial intelligence, air and space borne command & control, weather and environmental management, information technology, information assurance, and homeland security.

Missile Systems (21% of sales and 19% of profits) makes and supports a broad range of leading-edge missile systems for the armed forces of the U.S. and other countries. Business areas include naval weapon systems, which provides defensive missiles and guided projectiles to the navies of over 30 countries; air warfare systems, with products focused on air and ground-based targets, including the Tomahawk cruise missile; land combat, which includes the Javelin anti-tank missile; and other programs.

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[4] (Raytheon Company 2010)

[5] (Standard & Poor's 2010)

Network Centric Systems (18% of sales and 18% of profits) makes mission solutions for networking, command and control, battle space awareness, and transportation management. Business areas include combat systems, which provides ground-based surveillance systems; integrated communication systems; command and control systems; Thales-Raytheon Systems, a joint venture between the two companies; and precision technologies and components, which provides a broad range of imaging capabilities.

Space & Airborne Systems (17% of sales and 19% of profits) makes integrated systems and solutions for advanced missions, including traditional and non-traditional intelligence, surveillance and reconnaissance, precision engagement, unmanned aerial operations, Special Forces operations, and space. SAS provides electro-optic/infrared sensors, airborne radars for surveillance and fire control applications, lasers, precision guidance systems, electronic warfare systems and space-qualified systems for civilian and military applications.

Technical Services (10% sales and 6% profits) provides technical, scientific, and professional services for defense, federal government and commercial customers worldwide, specializing in mission support, counter-proliferation and counter-terrorism, range operations, product support, homeland security solutions, and customized engineering services.

2.1.1 Raytheon Intelligence and Information Systems

Raytheon Intelligence and Information Systems (IIS) is a leading provider of intelligence and information solutions that provide the right knowledge at the right time, enabling their customers to make timely and accurate decisions to achieve mission goals of national significance. As shown in Figure 1, their leading edge solutions include integrated ground control, cyber security, environmental (weather, water, &climate), intelligence, and homeland security.

Figure 1: Overview of Raytheon's Intelligence and Information Systems [6]

There are 9,200 employees at various IIS sites, which are shown in Figure 2. The headquarters of IIS, which is located in Garland, TX, consumes about 42% of the total IIS energy consumption, as shown in Figure 3. Eighty percent of IIS employees have received security clearances from the US government. The secret nature of the IIS business is important in that most areas of the company are considered a Sensitive Compartmented Information Facility (SCIF); therefore, information and data is not easily allowed to be taken in and out of the data centers. In addition, data centers that are considered SCIFs must be essentially self-sustaining. As the Physical Security Standards for Special Access Program Facilities states[7], "walls, floor and ceiling will be permanently constructed and attached to each other. To provide visual evidence of attempted entry, all construction, to include above the false ceiling and below a raised floor, must be done in such a manner as to provide visual evidence of unauthorized penetration."

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[6] (Raytheon Company 2009)

[7] (Joint Air Force - Army - Navy 2004)

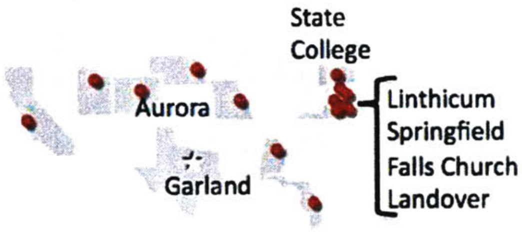

Figure 2: Overview of Major IIS Site Locations[8]

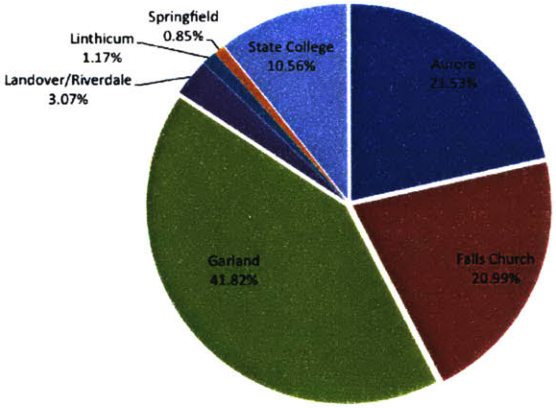

Figure 3: 2008 IIS Energy Consumption by Major Site

2.1.2 Background of Garland IIS Site

2.1.2.1 History of the Garland IIS Site[9]

The Garland site has been occupied since the 1950s. The site's legacy company - Texas Engineering and Manufacturing Company (TEMCO) – originally utilized the site, shown in Figure 4, to manufacture airframe components. However, the site's principal product had become systems engineering by the late 1950s. As shown in Figure 5, over the next three decades the site built additional buildings and changed ownership through mergers and acquisitions several times, before eventually becoming the headquarters of Raytheon Intelligence and Information Systems in May 1995 through a merger between E-Systems and Raytheon.

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[8] (Raytheon Company 2009)

[9] (Raytheon Company 2009)

Figure 4: Photo of the Garland site in the 1950s[10]

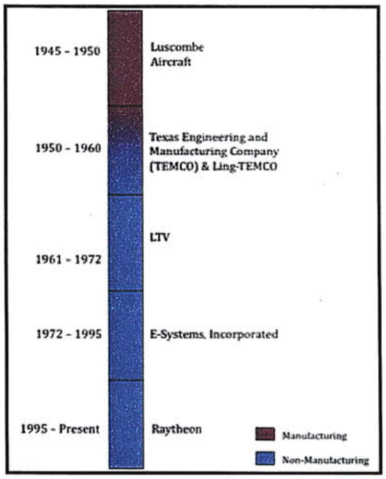

Figure 5: Timeline of the Garland Site[11]

2.1.2.2 Analysis of Garland's Electricity Consumption

The IIS Garland campus, shown in Figure 6, encompasses 1.142 million square feet and is home to 2,600 employees, contractors, and visitors.[12] An instantaneous analysis of electricity was completed in conjunction with the utility provider; Garland Power and Light, to better understand which buildings on the Garland campus used the majority of the electricity. As shown in Figure 7, the major buildings (551, 552, 580, 582, and 584) consume about 92% of the electricity, and no one building could be considered the primary electricity consumer on the Garland site. Additional analysis, as described in Appendix I – Process for Analyzing Energy Usage, was completed using past electricity data, so that we could better understand how electricity is consumed on the Garland site.

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[10] (Raytheon Company n.d.)

[11] (Raytheon Company n.d.)

[12] (The Raytheon Corportation n.d.)

Figure 6: Garland IIS Campus, circa 2009[13]

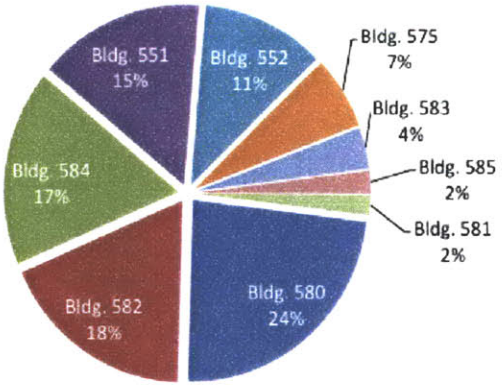

Figure 7: Breakdown of Garland electricity consumption (instantaneous reading)

As shown in Figure 8, the constant plug load makes up the majority of the energy consumed at Garland. To be the leading provider of intelligence and information solutions, Raytheon Intelligence and Information Systems (IIS) must have the latest computer equipment, particularly in their data centers. Therefore, the constant plug load in the data centers is comprised of IT equipment, cooling equipment used to remove the heat produced by the IT equipment, lighting, and electricity loss that results from transformers. In addition, emergency lighting and required evacuation systems are responsible for constant electricity consumption, albeit a minor amount. Finally, it is likely that some employees leave equipment – both intentionally due to program requirements and unintentionally due to long standing behavior patterns – turned on 24 hours, and this equipment is included in the constant load. The total constant plug load for Garland is about 5,200 kW per hour, and is about 89% of the total electricity consumed annually at the Garland site.

A varying amount of electricity, labeled "February Daily Load" and "June Daily Load" in Figure 8, is consumed each weekday as IIS employees at the Garland site use computers, printers, and other equipment. As shown in Figure 8, this daily load, which is considered the variable plug load, is consistently about 1000 kW per hour every month of the year in 2009, and is about 7% of the total electricity consumed at the Garland site.

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[13] (Google Maps n.d.)

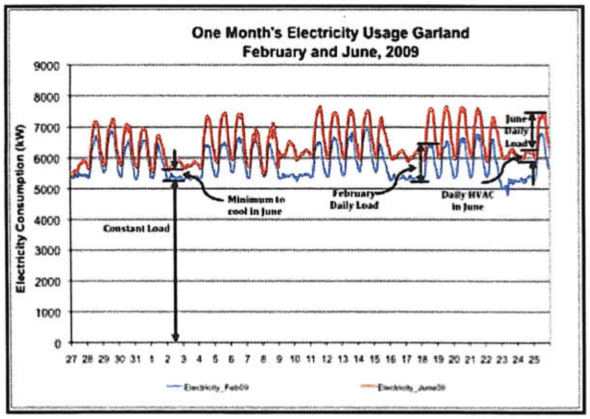

Figure 8: Illustration of Electricity Analysis performed for the Garland Campus

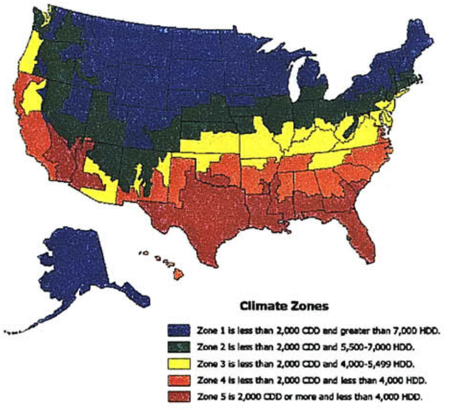

Figure 9: US Climate Zones for 2003[14]

The final consumer of electricity at the Garland site is the Heating, Ventilating, and Air Conditioning (HVAC) systems. As shown in Figure 8, the amount of electricity consumed in February is lower every hour than the electricity consumed in June. The minimum amount of electricity consumed in June is higher than the minimum electricity consumed in February due to the HVAC required to cool the buildings at all times, even weekends and nights. The increased weekend cooling requirements in June (as well as any non-winter month) are due to the extremely hot weather in Garland, as shown in Figure 9. The electricity required to achieve this minimum cooling varies month to month, and is illustrated as "Minimum to cool in June" in Figure 8. In addition to a minimum amount of cooling, HVAC is required to keep occupants comfortable while they are working at the Garland site. To determine how much electricity was required to achieve this "comfort cooling", the weekend electricity during June was observed, as shown in Figure 8. The total HVAC, which is the summation of the "minimum cooling" and "HVAC cooling" each month, averages about 555 kW per hour, and is about 4% of the total electricity consumed at the Garland site.

2.1.2.3 Analysis of Garland's Natural Gas Consumption

Natural gas is used at the Garland site for two primary purposes – hot water heating and occupant comfort (heating) during the winter months. Analysis similar to the analysis performed on electricity was performed on the Garland natural gas data to determine the amount of energy that is used for each purpose. As shown in Figure 10, the minimum amount of natural gas is consumed during the summer months, and is about 200 MWh monthly (approximately 277 kW per hour). Since a minimal amount of heating is required in the summer months at Garland for occupants' comfort, it is likely

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[14] (Energy Information Administration 2003)

that almost all of this natural gas consumption is for hot water heating. The remainder of the natural gas consumed each month is attributed to heating required to achieve occupants' comfort. It is notable that in some summer months, natural gas is consumed at a much higher level than the minimum required for hot water production. This is an indication that the HVAC system is over-cooling some areas of the Garland site, and occupants are "correcting" this mistake by turning on the heat in those areas. As shown in Figure 10, a minimal amount of "correcting" took place in the summer months of 2007; however, an increased consumption took place in the summer months of 2008. This could be a signal that the HVAC system's controls were not utilized as much in 2008 as they were in 2007. Finally, as shown in Figure 11, the total amount of natural gas is relatively small compared to the amount of electricity consumed at Garland.

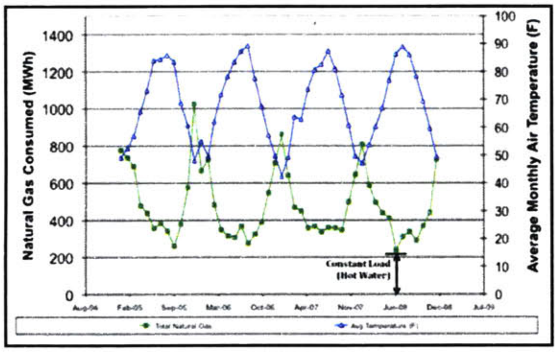

Figure 10: Garland Natural Gas Consumption, 2005- 2008

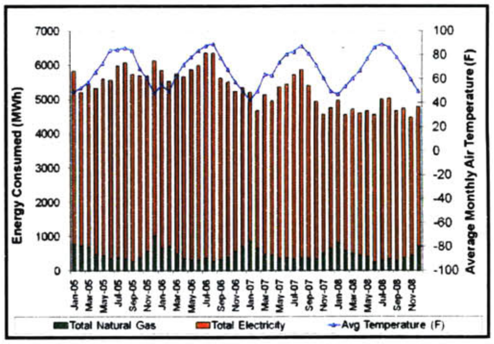

Figure 11: Garland Natural Gas and Electricity Consumption, 2005- 2008

2.1.2.4 Summary of Garland's Energy Consumption

The results of the analysis of both electricity and natural gas consumption were compiled, as shown in Table 1 and Figure 12. It is clear from Table 1 that the constant plug load, which results from data centers, equipment turned on 24 hours each day, and emergency lighting, is responsible for the majority of Garland's energy consumption. The HVAC system, utilized for occupants' comfort, is also responsible for a significant amount of energy consumption at Garland, while daily plug load and natural gas used for hot water heating are responsible for a very small amount of energy consumption.

Table 1: Percentage of Load Consumed at the Garland Site from 2005-2009

	Constant Load	HVAC (Gas + Electricity)	Gas for Water Heating	Daily Plug Load
2005	73%	18%	5%	4%
2006	79%	13%	5%	3%
2007	69%	20%	7%	4%
2008	77%	13%	5%	5%

The past four years of Garland energy consumption was obtained and analyzed. As shown in Figure 13, Garland was able to reduce their energy consumption by 21% from 2006-2008, indicating that an emphasis was placed on energy consumption during this period. Facilities employees and leadership confirmed this hypothesis during conversations stating, "our buildings are older, and we replaced some of the original lights and chillers the past few years. In addition, we installed instantaneous hot water heaters [in 2008], which also led to a substantial decrease in energy consumption. Finally, IIS recently began using more energy efficiently monitors, computers, and data center equipment, which also had an impact on the energy reduction achieved from 2006-2008. We keep updating the memory, processors, and other data center equipment…with each upgrade to more energy efficiency products, I'm sure we are reducing our constant load."

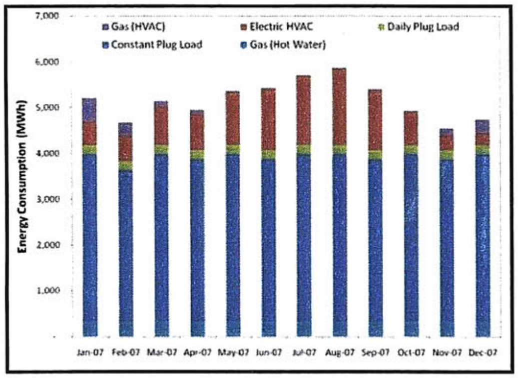

Figure 12: Example of energy consumption over a one year period at the Garland IIS site

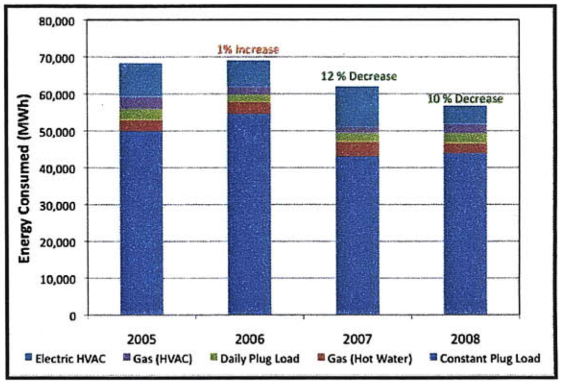

Figure 13: Breakdown of Garland energy consumption, 2005-2009

From the analysis of the energy consumed at Garland, it is obvious that the constant load deserves special attention. Since the majority of the constant load is related to data centers, a thorough process for improving the operating energy efficiency was developed and piloted using industry best practices.

2.2 Data Center Overview

2.2.1 Introduction

Even though most consumers do not know what a data center is, anyone who accesses the Internet uses data centers. As shown in Figure 14, a data center is a room that contains "Information Technology Equipment" – data processing electronic equipment such as servers, network equipment, and storage devices (memory). This electronic equipment is arranged in racks, as shown in Figure 15. Practically all companies in all sectors of the economy have at least one data center and many companies have multiple data centers to ensure required computing can occur. For example, if a company's employees have access to the internet, have a company email address, or store files on a company file server, than the company likely has data centers that support their computing infrastructure.

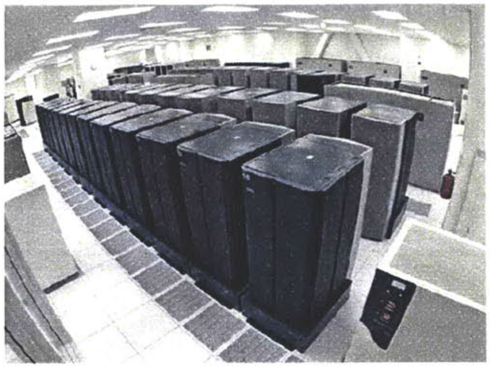

Figure 14: Example of a data center[15]

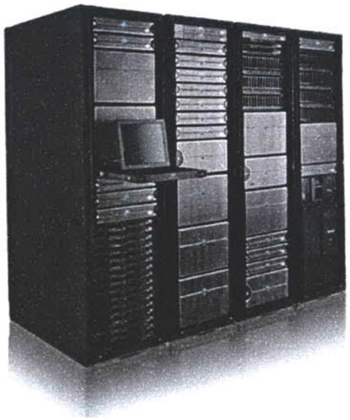

Figure 15: Example of racks contained in a data center[16]

Because data centers are used to house computing equipment, they typically have no windows and have a minimum amount of incoming fresh air. Data centers range in size from small rooms (server closets) within a conventional building to large buildings (enterprise class data centers) dedicated to housing servers, storage devices, and network equipment.[17] Large data centers are becoming increasingly common as smaller data centers consolidate.[18] In addition, in most cases data centers are used for many years, resulting in a mixture of state-of-art and obsolete computing equipment.

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[15] (Lawrence Berkeley National Laboratory 2003)

[16] (System Energy Efficiency Lab n.d.)

[17] (US Environmental Protection Agency 2007)

[18] (Carr 2005)

2.2.2 Typical Electricity usage within a Data Center

There are several components required to ensure a data center operates correctly, as shown in Figure 16. Each of the components consumes electricity, and can be grouped into three categories - power delivery, IT equipment, and heat removal (or cooling equipment). Additionally, miscellaneous equipment consumes a relatively small amount of electricity. The amount of electricity consumed by each component varies between data centers. Even the "typical" consumption varies by source, as shown in Figure 17. Generally, the IT equipment and the cooling equipment required to remove heat generated inside the data center consume the bulk of the electricity. However, the power delivery system consumes a substantial amount of electricity, especially in older data centers.

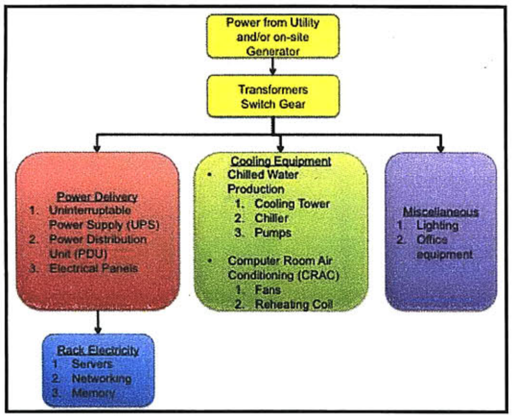

Figure 16: Diagram of the Electricity Flow into a Data Center

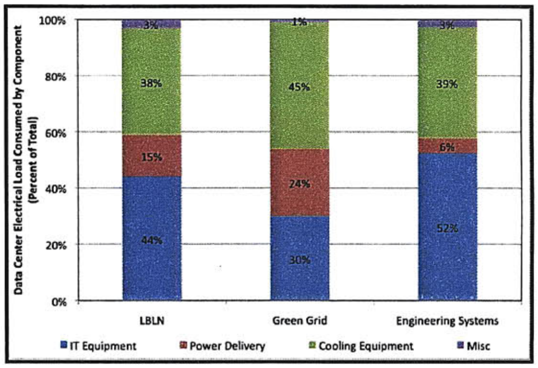

Figure 17: Typical Electricity Consumption of a Data Center[19,20,21]

Because the efficiency of each component and subcomponent has a direct impact on the overall efficiency of the data center, an understanding of how each component consumes electricity is beneficial.

2.2.2.1 Electricity Required to Deliver Power

The first electricity requirement for a data center is the power delivery system that supplies electricity to the IT equipment, cooling equipment, and miscellaneous equipment. A local utility and/or an on-site electrical generator supplies electricity, which is sent to the building that contains the data center

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[19] (Rasmussen, Avoidable Mistakes that Compromise Cooling Performance in Data Centers and Network Rooms 2008)

[20] (The Green Grid 2007)

[21] (Salim 2009)

through transformers and switchgears. The electricity is then sent to an uninterruptible power supply (UPS), which is essentially a set of batteries that ensure that electricity is always available to the data center. This uninterruptible supply of electricity is important because most data centers operate 24 hours a day, 7 days a week. However, grid disruptions can stop the supply of electricity from the utility, making the UPS a key component of the power delivery system. As shown in Figure 18, electricity is transformed from the UPS to the power distribution unit (PDU), which then sends the electricity to the electrical panels that supply electricity to the data center IT equipment.

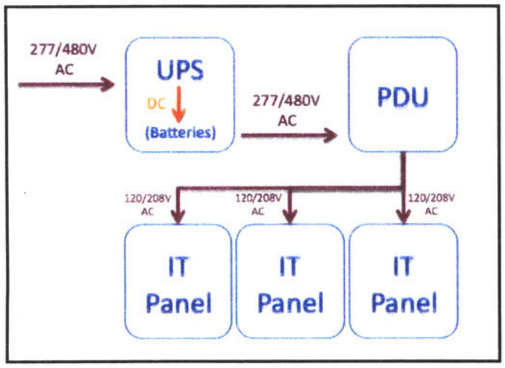

Figure 18: Diagram of Electricity Flow through the Power Delivery System[22,23]

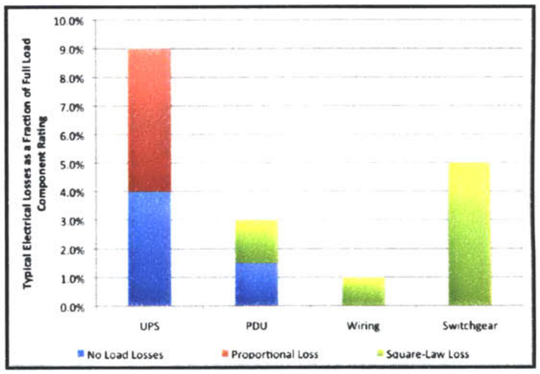

Figure 19: Typical Electricity Consumption of a Data Center[24]

As shown in Figure 18, in the UPS the electricity is converted from AC to DC to charge the batteries. Power from the batteries is then reconverted from DC to AC before leaving the UPS. Electricity consumed in this power delivery chain accounts for a substantial portion of overall building load.[25] Inherent losses are present for the power delivery system, as shown in Figure 19, and increase if the components used are oversized for the data center they are serving.

2.2.2.2 Electricity Required for IT Equipment

Three primary types of IT equipment comprise a data center: servers, storage devices, and network equipment. As shown in Figure 20, servers account for about 75% of the electricity consumed by data center equipment, while storage devices and networking equipment account for 15% and 10%, respectively, of the electricity consumed.

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[22] (Rasumssen 2006)

[23] (US Environmental Protection Agency 2007)

[24] (Rasmussen, Electrical Efficiency Modeling of Data Centers 2006)

[25] (US Environmental Protection Agency 2007)

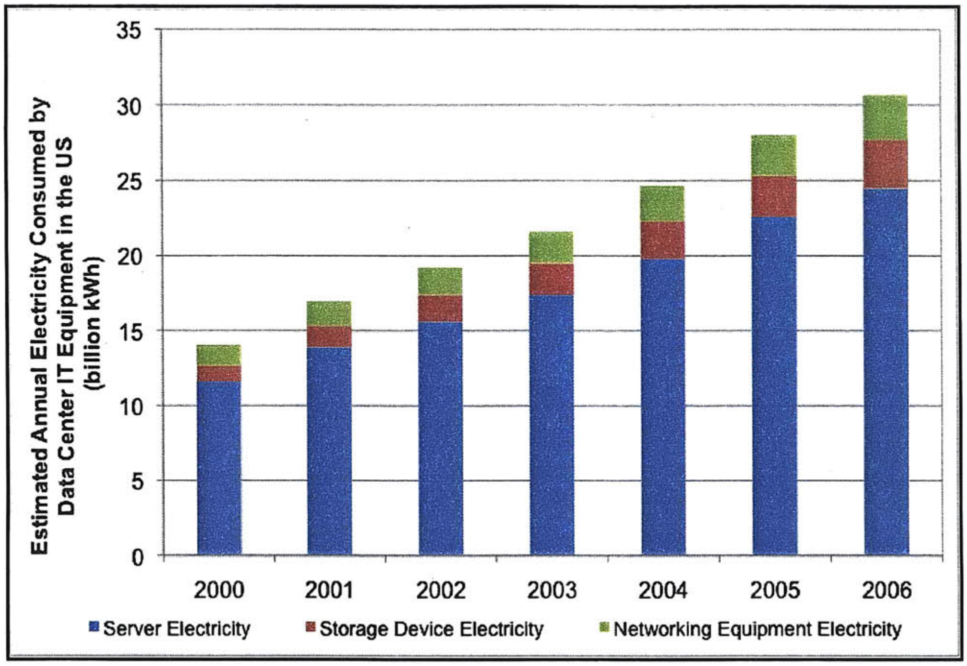

Figure 20: Estimated Electricity Consumed by the IT Equipment in US Data Centers from 2000-2006[26]

As electricity is consumed by IT equipment, heat is generated. Approximately 50% of the heat energy released by servers originates in the microprocessor itself, and over 99% of the electricity used to power IT equipment is converted into heat.[27] Therefore, it is very important to understand how this heat is removed, and how electricity is consumed during the heat removal process.

2.2.2.3 Electricity Required to Remove Heat

In order to keep the components of data center IT equipment within the manufacturers' specified temperature and humidity range, heat produced within the data center must be removed. If the IT equipment is not kept within the manufacturers' specified limits, the equipment's reliability is reduced.

To put the heat load that must be removed from data centers in perspective, a fully populated rack of blade servers consumes 30 kW of electricity (720 kW per day)[28], which is the equivalent of 43 average

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[26] (US Environmental Protection Agency 2007)

[27] (Evans, Fundamental Principles of Air Conditioners for Information Technology 2004)

[28] (Hughes 2005)

US homes.[29] All of this electric power is converted to heat, which must be removed from the data center. In addition to IT equipment, other data center components, as shown in Figure 21, generate heat that must be removed from the data center. In total about 42 kWh (143,310 BTUs) of heat is produced daily that must be removed from the data center.

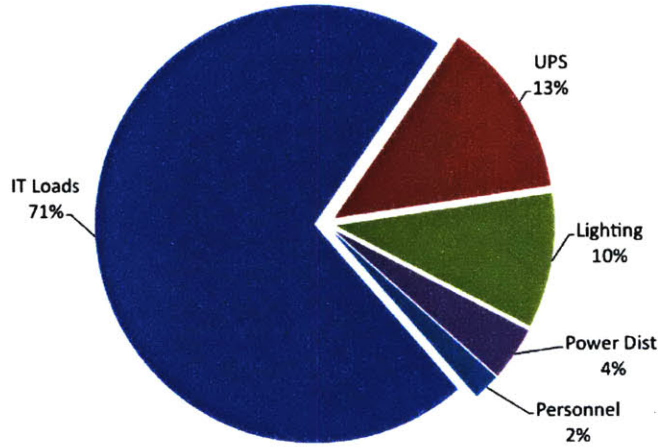

Figure 21: Relative contributions to the total thermal output of a typical data center[30]

There are five basic methods to collect and transport unwanted heat from the IT environment to the outdoor environment, and each method uses the refrigeration cycle to transport or *pump* heat from the data center:[31]

- Air cooled systems (2-piece)
- Air cooled self-contained systems (1-piece)
- Glycol cooled systems
- Water cooled systems
- Chilled water systems

The five methods are primarily differentiated in the way they physically reside in the IT environment and in the medium they use to collect and transport heat to the outside atmosphere. Obviously, each method has advantages and disadvantages. The decision on which cooling system to choose should be based on the uptime requirements, power density, geographic location and physical size of the IT

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[29] (US Energy Information Administration 2009)

[30] (Evans, The Different Types of Air Conditioning Equipment for IT Environments 2004)

[31] (Evans, Fundamental Principles of Air Conditioners for Information Technology 2004)

environment to be protected, the availability and reliability of existing building systems, and the time and money available for system design and installation.[32]

Most large data centers use chilled water systems to remove the heat from data centers, as shown in Figure 22. Heat generated in the data center is transported to the top of the computer room air conditioner (CRAC) by the air circulating in the data center. The condenser coil then uses chilled water to complete the refrigeration process, which is shown in Figure 23, on the heated air.

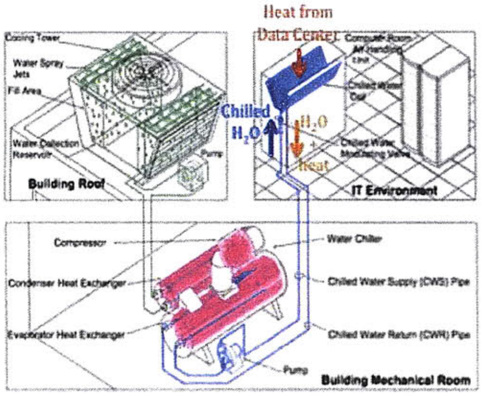

Figure 22: Diagram of a Chilled Water System used to Remove Heat from a Data Center[33]

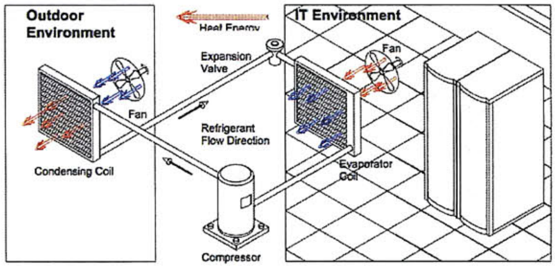

Figure 23: Heat Energy Removal Via the Refrigeration Cycle[34]

The major consumers of electricity of the heat removal system are the pumps used to transport the heat-carrying medium from the data center to the outside atmosphere, the computer room air conditioners (CRAC), and the ongoing upkeep/production of the heat-carrying medium. The amount of electricity these consumers use is different for each system. For example, the chilled water system uses electricity to pump the water from the cooling tower to the water chiller, to pump the chilled water from the water chiller to the CRAC, and to pump the warm water from the CRAC to the outside atmosphere. In addition to pumping water, the CRAC uses electricity to reheat air if the humidity of incoming air from the data center is too low. Finally, electricity is used to reduce the temperature of the water both in the cooling tower and in the water chiller.

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[32] (Evans, Fundamental Principles of Air Conditioners for Information Technology 2004)

[33] (Evans, The Different Types of Air Conditioning Equipment for IT Environments 2004)

[34] (Evans, Fundamental Principles of Air Conditioners for Information Technology 2004)

Estimates of the electricity required for the pumps and chilled water production, and the computer room air conditioner vary by data center, as shown in Figure 24. The difference in electricity breakdown depends on the efficiency, age, and level of maintenance of all the components of the heat removal system (cooling tower, pumps, water chiller, fans, etc). In addition, the efficiency depends on how efficient heat generated from the IT equipment is transported to the CRAC units.

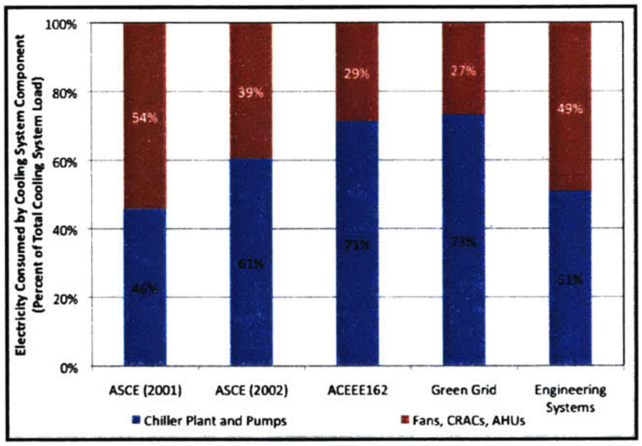

Figure 24: Typical Electricity Consumption of by the heat removal system of a Data Center[35,36,37,38]

2.2.3 Impact of Data Centers

Most data centers are more energy intensive than other buildings. This is due to the high power requirements of the IT equipment and the power and cooling infrastructure needed to support this equipment. In fact, data centers can be more than 40 times as energy intensive as conventional office buildings.[39] As an aggregate in 2005, data centers accounted for 1.5% of the total US electricity consumption and 0.8% of the total world electricity consumption.[40] To put this in perspective, in 2007 the carbon dioxide emitted because of data center energy consumption was more than the carbon dioxide emitted by both Argentina and the Netherlands.[41] This percentage of total electricity consumed – and therefore the impact of data centers – is expected to increase over the next decade for various reasons, such as:

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[35] (Blazek, et al. 2004)

[36] (Tschudi, et al. 2003)

[37] (The Green Grid 2007)

[38] (Salim 2009)

[39] (Greenburg, et al. 2007)

[40] (Koomey 2007)

[41] (Kaplan, Forrest and Kindler 2008)

- Industries (banking, medical, finance, etc.) moving from paper records to electronic records.
- Increased use of electronic equipment, such as global positioning system (GPS) navigation and radio-frequency identification (RFID) tracking in everyday activities.
- Increased access to information technology in developing countries such as India, China, etc.
- Increased storage of records (both original and duplicates) for websites, databases, emails, etc.

As the move to a digital way of life continues, the electricity consumed by data centers will increase as shown in Figure 25.

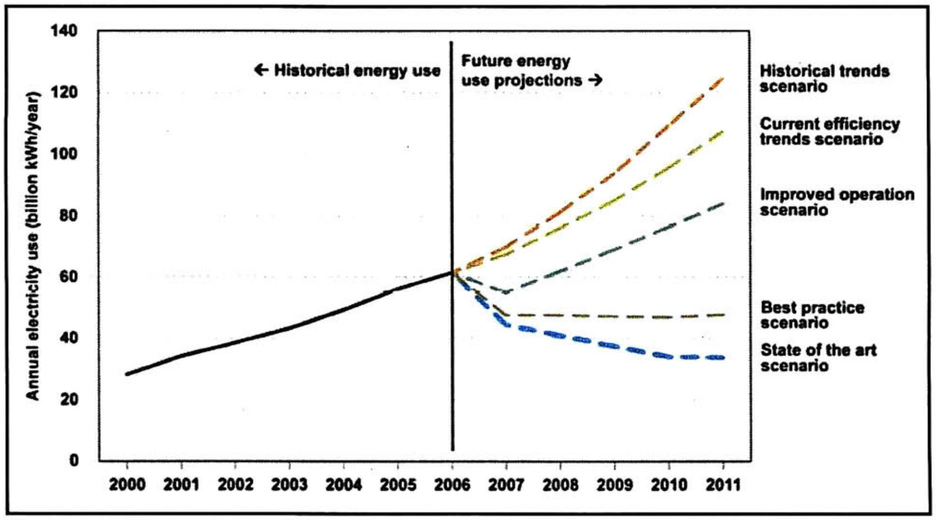

Figure 25: Projected Electricity Usage of Data Centers for Different Scenarios[42]

As illustrated in Figure 25, the level of efficiency, both in the IT equipment and the data center operating principles will have an enormous impact on how much electricity data centers consume. The different assumptions for each efficiency scenarios can be seen in Appendix II – Summary of Alternative Efficiency Scenario Assumptions.

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[42] (US Environmental Protection Agency 2007)

3 Hypothesis

The energy efficiency of existing data centers can be increased substantially through relatively low-cost changes. However, the changes involve not only technical acumen, but also require leadership support and employee engagement. Moreover, the energy consuming behaviors of working professionals can be changed through a simple behavior change model of providing feedback, incentives, and reinforcement in sequential order.

4 Methodology

4.1 Data Collection and Analysis

In order to develop and test a data center improvement process, a three-step process was used:

1. Research industry best practices and develop an initial improvement process (as discussed in this section).
2. Test the improvement process on a pilot data center in Garland (as discussed in the Chapter 5).
3. Integrate lessons learned into the initial improvement process (as discussed in Chapter 6).

In order to measure the affect of the improvement process, data was collected prior to, during, and after the implementation of the improvement process.

4.2 Review of Industry Best Practices

There is no shortage of suggestions for improved energy efficiency of data centers available in white papers, top ten lists, and various reports. Entire conferences are dedicated to the energy efficiency of data centers.[43] This illustrates that there are many ways to improve the energy efficiency of data centers, a sampling of which can be seen in Table 2. However, the changes required vary in cost and impact depending on the baseline efficiency of the data center. While medium and high-cost techniques are reviewed herein, the emphasis of this thesis is to develop a low-cost improvement process. Therefore, an emphasis is placed on techniques that required minimal budget and time to implement. The improvement opportunities are categorized by the energy component of the data center they impact, namely power delivery, information technology (IT) equipment, heat removal equipment, and miscellaneous equipment.

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[43] An example can be seen at http://greendatacenterconference.com/

Table 2: Overview of Strategies for Reducing Date Center Electricity Consumption

Data Center Component	Improvement Description	Capital Required[1]	Labor Required[1]	Behavior Change[1]	Savings[2]
Power Supply	Rightsizing	🟥	🟥	🟥	10-30%
Power Supply	Add on-site power generation to reduce or eliminate UPS	🟥	🟥	⬛	2-7%[3]
Power Supply	Improved UPS	🟥	⬛	⬛	4-10%
IT Equipment	Consolidation	🟥	🟥	🟥	unknown
IT Equipment	Replace obsolete equipment	🟥	🟥	🟥	30-50%
IT Equipment	Virtualization	🟥	⬛	🟥	10-40%
IT Equipment	Manage power	⬛	⬛	🟥	
Heat Removal	Use in-rack water cooling	🟥	🟥	🟥	7-15%
Heat Removal	Use Cooling Economizer	🟥	🟥	⬛	4-15%
Heat Removal	Improve airflow management	⬛	⬛	🟥	16-51%[4]
Miscellaneous	Install Energy Efficient Lighting	🟨	🟨	🟨	1-3%

[1] Red = "Yes", Yellow = "In some Instances", Green = "No"

[2] (Rasmussen, Implementing Energy Efficient Data Centers 2006)

[3] Assumed inefficiency of UPS was eliminated (Rasmussen, Implementing Energy Efficient Data Centers 2006)

[4] Sum of More Efficient Air Conditioner Architecture, More Efficient Floor Layout, Coordinate Air Conditioners, Locate Vented Floor Tiles Correctly, Reduce Gaps between racks/floors/walls, and Install Blanking Panels and Floor Grommets

4.2.1 Power Delivery Equipment Energy Efficiency

Three ways to increase the efficiency of the power supply equipment will be discussed in detail in the following sections. Unfortunately, none of these three techniques were used for the pilot data center because they require capital and/or the methods discussed must be performed during the design phase of a data center, rather than during a retrofit or upgrade.

4.2.1.1 Rightsizing the Data Center

Of all the techniques available to increase the efficiency of data centers, rightsizing the physical infrastructure to the IT load has the most impact on electrical consumption, with savings of up to 50% observed in some cases.[44] Once the data center is set-up and running, it is nearly impossible to retrofit the power delivery equipment and the heat removal equipment to the actual requirements. Therefore, rightsizing must be performed in the design stages of a data center.

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[44] (The Green Grid 2007)

As the name implies, rightsizing is the process of ensuring the power delivery system is designed to supply the IT equipment with the electricity it requires. While it sounds very simple, rightsizing is very difficult because the average load requirements that will be present once the IT equipment is purchased and installed depends on many factors, such as rack configuration and eventual use of the equipment. Therefore, many data center managers design the data center for the maximum theoretical load of the equipment to ensure that their infrastructure can handle the worst-case scenario. However, the reality is that most data centers operate well below their maximum load, which will be discussed in Section 4.2.1.3. Therefore, a better design practice would be to size electrical and mechanical systems such that they will operate efficiently while overall loading is well below design, yet be scalable to accommodate larger loads should they develop.[45] To further assist in rightsizing, many manufacturers of servers, storage devices, and networking equipment offer programs that will calculate the typical load depending on the configuration of the racks in the data center. An example of such software is shown in Figure 26.

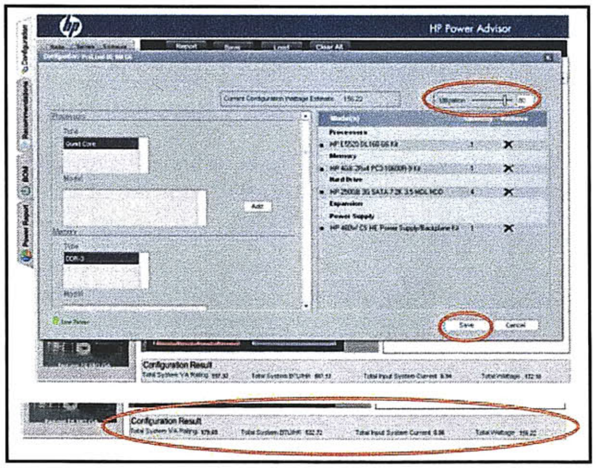

Figure 26: Screen shot of HP Power Advisor, which helps customers estimate the load of future racks in their data centers[46]

As shown in Figure 26, the user of the software is able to input what servers, storage devices, and networking equipment will comprise their racks. In addition, the user is able to estimate utilization of the rack, so that a realistic estimate of the typical power requirements can be determined. If this type of process is used to design the entire data center, the energy efficiency will be improved.

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[45] (Greenburg, et al. 2007)

[46] (HP 2009)

Indeed, this system design approach has a much greater effect on the electrical consumption than does the efficiency of individual devices.[47] A table of other calculators can be seen in Appendix III – List of Electrical Power Calculation Tools.

In addition, to better estimating the future IT equipment load, the data center can be designed not only to accommodate current requirements, but also to allow for future growth if required. Indeed, planning for the present and the future can improve overall system efficiency. Examples of adding redundant capacity and sizing for true peak loads are as follows:[48]

- Upsize duct/plenum and piping infrastructure used to supply cooling to the data center.
- Utilize variable-speed motor drives on chillers, pumps for chilled and condenser water, and cooling tower fans.
- Pursue efficient design techniques such as medium-temperature cooling loops and waterside free cooling.
- Upsize cooling towers so that chiller performance is improved.

4.2.1.2 On-site Power Generation

The combination of a nearly constant electrical load and the need for a high degree of reliability make large data centers well suited for on-site generation.[49] If onsite generation is utilized for data centers, the need to have back-up power standing by, namely the battery charged UPS, is eliminated. Since the UPS consumes 6-18% of the total data center electricity and generates heat that must be removed, savings from utilizing on-site generation can be substantial. In addition, on-site generation equipment could replace any currently utilized backup generator system. There are several important principles to consider for on-site generation:[50]

- On-site generation, including gas-fired reciprocating engines, micro-turbines, and fuel cells, improves overall efficiency by allowing the capture and use of waste heat.
- Waste heat can be used to supply cooling required by the data center with absorption or adsorption chillers, reducing chilled water plant energy costs by well over 50%. In most situations, the use of waste heat is required to make site generation financially attractive. This strategy reduces the overall electrical energy requirements of the mechanical system by

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[47] (The Green Grid 2007)

[48] (Greenburg, et al. 2007)

[49] (Tschudi, et al. 2003)

[50] (Greenburg, et al. 2007)

eliminating electricity use from the thermal component, leaving only the electricity requirements of the auxiliary pump and motor loads.

- High-reliability generation systems can be sized and designed to be the primary power source while utilizing the grid as a backup. Natural gas used as a fuel can be backed up by propane.
- Where local utilities allow, surplus power can be sold back into the grid to offset the cost of the generating equipment. Currently, the controls and utility coordination required to configure a data center-suitable generating system for sellback can be complex; however, but efforts are underway in many localities to simplify the process.

4.2.1.3 Improve the Operating Efficiency of the UPS

There are two fundamental ways to increase the operating efficiency of a UPS. The first is to simply purchase a new, best-in-class UPS, which as shown in Figure 27, has 70% less losses than a legacy UPS at typical loads.[51] The second way to increase the operating efficiency of a UPS is to load the UPS in such a way to maximize efficiency. As shown in Figure 28, the efficiency of the UPS depends on the difference in the IT load and the capacity of the UPS. The closer the load is to the capacity, or full power rating of the UPS, the lesser the amount of electricity that will be wasted due to inefficiency. To increase the load on the UPS, the load of two or more data centers may be combined and served from one on-site UPS, assuming more than one data center exists.

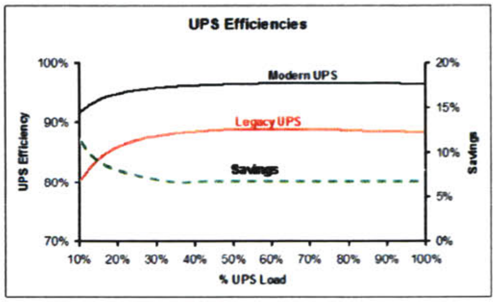

Figure 27: UPS efficiency as a function of load comparing latest generation UPS to historic published data[52]

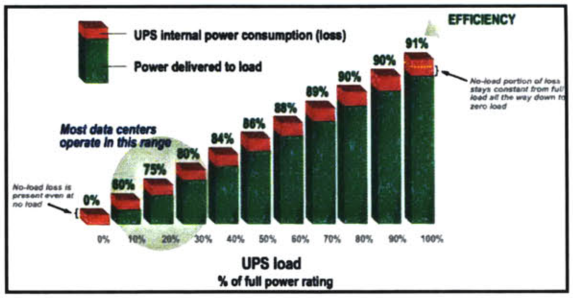

Figure 28: Effect of internal UPS loss on Efficiency[53]

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[51] (Rasmussen, Implementing Energy Efficient Data Centers 2006)

[52] (The Green Grid 2009)

[53] (Rasmussen, Electrical Efficiency Modeling of Data Centers 2006)

4.2.2 IT Equipment Energy Efficiency

Four ways to increase the efficiency of the IT equipment will be discussed in detail in the following sections. As with the power delivery system, none of the methods discussed were used for the pilot data center because they require capital and/or because existing contracts, under which Raytheon IIS completes its work, do not allow IT equipment to be consolidated.

4.2.2.1 Replace and/or Remove Obsolete Equipment

If those servers currently being utilized in data centers were replaced with new, energy efficient servers, 25% less energy would be consumed across a range of typical processor utilization levels.[54] It is clear that with servers, as with other technology, the energy efficiency increases with almost every new release. However, unlike other technology, each new release is more powerful and capable of higher computer performance, even though the size of the component is roughly the same. For example, microprocessor performance improved 50% per year from 1986 to 2002.[55] Most of the major server and processor companies are now touting improved performance per watt – performance improvements of 35% to 150% or more over previous generations.[56] This performance has lead to more power in a smaller amount of space, which has lead to an increase in power requirements and heat density of data centers. This increase in computing power has resulted in a higher power per unit, as shown in Figure 29, which is directly related to a higher heat output per unit. It is important to note that this heat must be removed from the data center by the heat removal equipment.

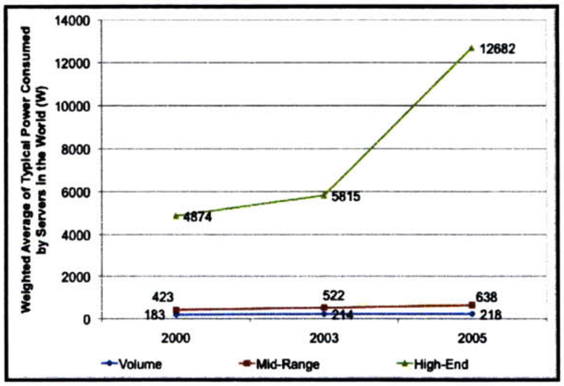

Figure 29: Typical power of servers in the world over time[57]

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[54] (US Environmental Protection Agency 2007)

[55] (Hennessy and Patterson 2007)

[56] (Loper and Parr 2007)

[57] (Koomey 2007)

Storage devices are also a substantial energy consumer in data centers and are becoming more important as more information is digitalized. Storage devices are so important that ENERGY STAR recently announced an initiative to develop an energy efficiency standard for data center storage devices.[58]

In addition to purchasing new servers, storage equipment, and networking equipment to replace obsolete equipment, data center managers can save a substantial amount of energy simply be removing old, unused IT equipment from their data center. Oftentimes, new servers are installed into data centers to replace old servers, but they often do not replace those servers immediately. Rather, there is a transition time in which both the old and new servers are in use. Once the transition is complete, the data center manager sometimes forgets to remove the old, unused server. These servers will almost never be utilized (with only the occasional spikes of utilization when standard housekeeping tasks - backups, virus scans, etc. – run); however, the machines continue to consume power and produce heat that must be removed.[59] Unused servers can be identified by analyzing network statistics, and should be decommissioned to save energy.[60]

4.2.2.2 Proactively Manage the Power Settings of the Equipment

There are two key components of energy management strategy for IT equipment. The first is to use power management settings on the equipment, and the second is to turn off equipment when it is not in use. Both of these tools can save a substantial amount of energy. For example, enabling power saving architecture, which comes standard on most new IT equipment, can result in overall power savings of up to 20%.[61] As shown in Figure 30, enabling power saving mode can have a drastic effect on the amount of power consumed by IT Equipment.

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[58] (Fanara 2009)

[59] (Blackburn 2008)

[60] (Blackburn 2008)

[61] (Blackburn 2008)

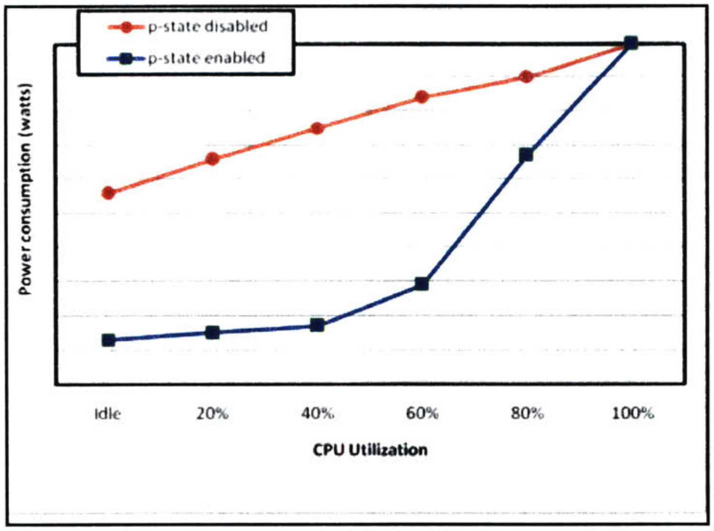

Figure 30: Comparison of Power Consumption when "Performance State" of AMD servers[62]

The second way to save energy using a power management strategy is to simply turn off equipment when it is not in use. Most IT equipment has the ability to completely shut down during a certain time of the day (for example, 6pm-8am), and/or for certain periods of the year (for example, the December holiday shutdown that many businesses have). However, in most cases the option must be turned on and managed closely by the data center manager.

4.2.2.3 Server Consolidation & Virtualization

As shown in Figure 31 and Figure 32, most servers typically operate in an energy inefficient range, in which they consume between 60 to 90% of their maximum system power.[63]

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[62] (Blackburn 2008)

[63] (US Environmental Protection Agency 2007)

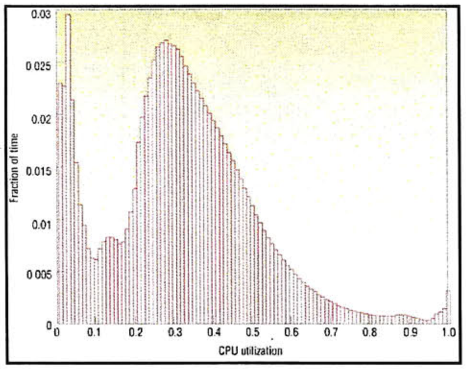

Figure 31: Average CPU utilization of more than 5,000 servers during a six-month period. Servers are rarely completely idle and seldom operate near their maximum utilization.[64]

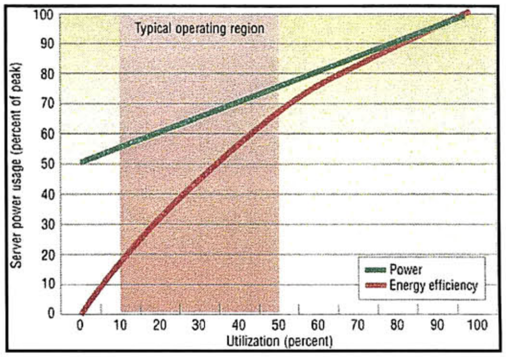

Figure 32: Server power usage and energy efficiency at varying utilization levels, from idle to peak performance. Even an energy-efficient server still consumes about half its full power when doing virtually no work.[65]

Two solutions exist to increase the utilization and thus energy efficiency of IT equipment – physical consolidation and computer consolidation (virtualization). Several examples of physical consolidation are shown in Figure 33. Physical consolidation increases both operating efficiency and heat removal efficiency since the consolidation increases the utilization of the servers in use, and allows data center managers to decrease the areas of the data center in which heat must be removed. In addition, some of the extremely underutilized servers may be able either decommissioned or used for a different application, saving the data center manager in energy usage and required expenditures for new servers.

Virtualization, as shown in Figure 34, is a type of consolidation that allows organizations to replace several dedicated servers that operate at a low average processor utilization level with a single "host" server that provides the same services and operates at a higher average utilization level.[66] Virtualization may offer significant energy savings for servers because although many services are only occasionally busy, the power consumed by the idle hardware is almost as much as the power required for active operation.[67] When these servers are virtualized, a smaller number of servers can provide significant energy savings because fewer servers are required to meet the computing

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[64] (Google 2007)

[65] (Google 2007)

[66] (US Environmental Protection Agency 2007)

[67] (Hirstius, Jarp and Nowak 2008)

requirements, and each of the servers operates at a higher utilization and therefore higher energy efficiency.

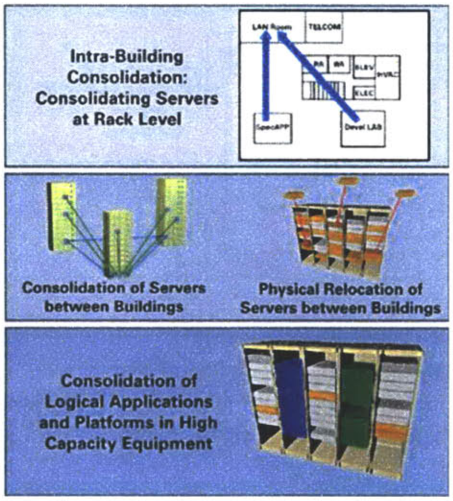

Figure 33: Various forms of consolidation[68]

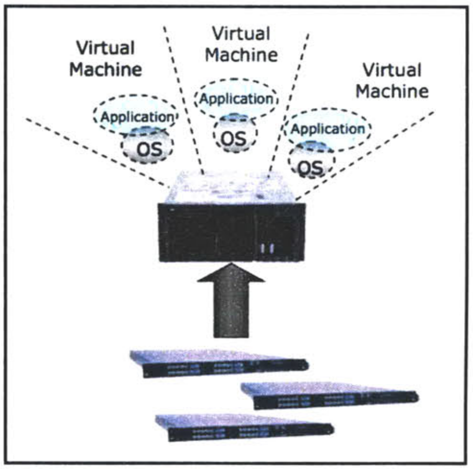

Figure 34: Diagram illustrating Virtualization[69]

4.2.3 Heat Removal Energy Efficiency

Improvements to the heat removal equipment can drastically affect the overall energy efficiency of a data center. Three ways to increase the efficiency of the heat removal equipment will be discussed in detail in the following sections. As with the previous improvement opportunities, "use in rack water cooling" and "use cooling economizers" require substantial capital and are difficult to implement in an existing data center. However, unlike the previous improvements, "improve airflow management," is low-cost and was utilized in the pilot data center.

4.2.3.1 Use In-rack Water Cooling

Liquid cooling, as shown in Figure 35, can be far more efficient for removing heat from data centers since it eliminates the mixing of cold and hot air, and due to the much higher volumetric specific heats and higher heat transfer coefficients of liquid.[70] For example, in large data centers, air cooling systems often require an amount of electricity equivalent to almost 100% of the IT load to remove

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[68] (American Power Conversion (APC) n.d.)

[69] (Williams 2006)

[70] (Greenburg, et al. 2007)

the heat; by contrast, chilled water systems will require only about 70% of the system wattage to remove the heat.[71]

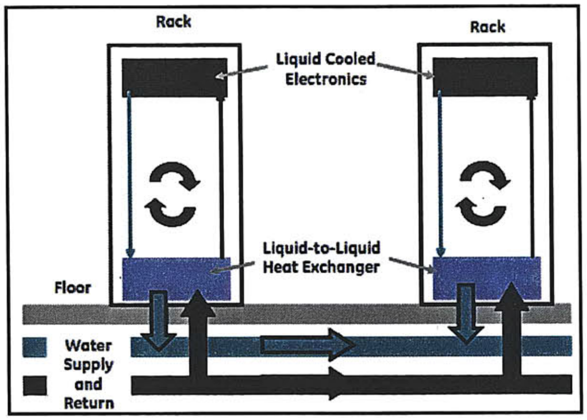

Figure 35: Example of how a liquid-cooling configuration could be configured in a data center[72]

There are three major barriers that must be overcome to make liquid cooling more prominent in data centers, as follows:

1) the established mindset that air cooling is the best practice in data centers.
2) the fear that liquid cooling can destroy equipment if failure occurs.
3) the new infrastructure, including a new plumbing system, which must be put into place to support a liquid cooling strategy.

If these barriers can be overcome or mitigated, the potential savings from direct, liquid cooling are substantial. Not only can the computer room air conditioners (CRAC) be eliminated, but also in some environments the water from a chilling tower is cold enough without mechanical chilling to remove the heat from data centers.[73]

4.2.3.2 Use Cooling Economizer

There are two types of cooling economizers that can be deployed in data centers (water-side and air-side) to reduce the electricity required by the data center. Water-side economizers save electricity by reducing the mechanical chilling of water required. This reduction is achieved by supplying chilled

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[71] (Sawyer 2004)

[72] (Hwang 2009)

[73] (Greenburg, et al. 2007)

water directly from a cooling tower to the CRAC units in order to remove heat from the data center, as shown in Figure 36.

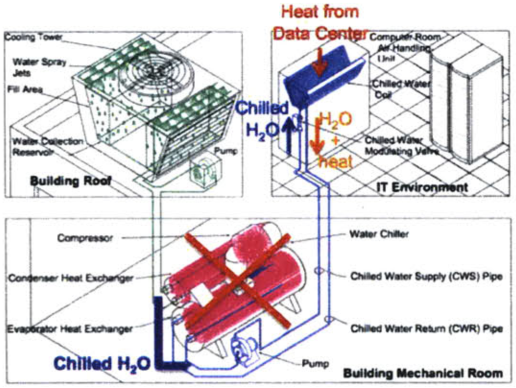

Figure 36: Diagram of a Chilled Water System using chilled water directly from the cooling tower to remove heat from the Data Center[74]

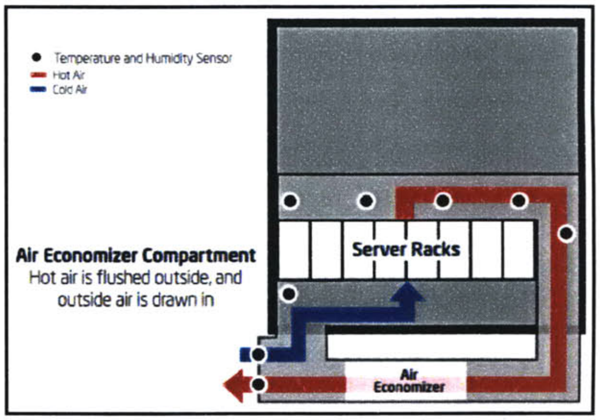

Figure 37: Diagram of a Data Center relying only on heat removal through an Air-Side Economizer[75]

Water-side economizers are best suited for climates that have wet bulb temperatures lower than 55°F for 3,000 or more hours per year, and can reduce the chilled water plant energy consumption by up to 75%.[76] While water-side economizers are considered low-risk by data center professionals, these same professionals are split on the risk when using air-side economizers.[77]

As shown in Figure 37, air-side economizers simply transport cool outside air into the data center instead of using chilled water to remove heat from the data center. Heat produced from the IT equipment is flushed outside. Two characteristics of the outside air raise concern with data center professionals – humidity and contamination. However, tests have shown that these fears may be unjustified, and that air-side economizers can reduce the electricity consumption of a data center by 60%.[78]

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[74] (Evans, The Different Types of Air Conditioning Equipment for IT Environments 2004)

[75] (Atwood and Miner 2008)

[76] (Greenburg, et al. 2007)

[77] (Greenburg, et al. 2007)

[78] (Atwood and Miner 2008)

4.2.3.3 Improve Airflow Management

The goal of air management in a data center is to separate the hot air generated from the IT equipment from the cold air that cools the IT equipment. Airflow management is one of the most practical ways to improve the overall energy efficiency of data centers, and very large increases in energy efficiency can result from robust airflow management. There are several reasons to resolve heat removal problems in the data center, as follows:[79]

- There are practical, feasible, and proven solutions.
- Many fixes can be implemented in existing data centers.
- Large improvements (20% or more) can result from little to no investment.
- Both IT people and facilities people can contribute to fixing the problem.
- Solutions are independent of facility or geographic location.
- They lend themselves to correction through policies that are simple to implement.

The potential solutions to heat removal problems are described below, and are organized from relatively difficult to easy solutions.

4.2.3.3.1 Floor Layout

If airflow is to be managed, the first step is to separate the hot air generated from the IT equipment from the cold air that is meant to cool the equipment. The first step that must be taken to achieve this is to design the data center in the correct layout. Eighteen percent of the total 51% savings in data center electricity is due to improving the floor layout, which includes hot/cold aisle arrangement and the location of perforated floor and ceiling tiles.[80]

4.2.3.3.1.1 Hot/Cold Aisle Configuration

As shown in Figure 38, if the racks containing IT equipment are not properly arranged, hot air from the racks mixes with the cold air coming from the raised floor, resulting in warm air entering the IT equipment. This warm air is not able to cool the IT equipment efficiently, which results in a requirement for colder air from the CRAC, which in turn requires additional chilled water and therefore electricity.

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[79] (Rasmussen, Avoidable Mistakes that Compromise Cooling Performance in Data Centers and Network Rooms 2008)

[80] (Rasmussen, Implementing Energy Efficient Data Centers 2006)

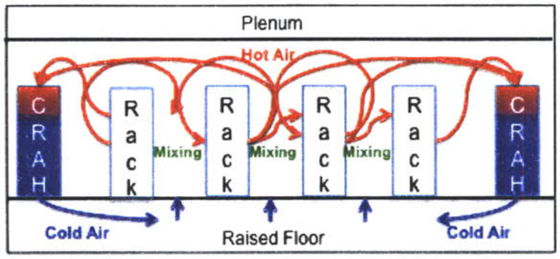

Figure 38: Rack arrangement without hot and cold aisles (side view) Red indicates hot air, while blue indicates cold air.

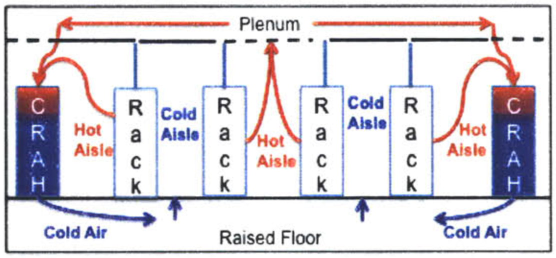

Figure 39: Hot/cold aisle rack arrangement (side view). Red indicates hot air, while blue indicates cold air.

Other problems exist in the arrangement shown in Figure 38. For example, because the hot air is not evacuated into the plenum, it must travel directly over the racks in order to return to the CRAC. As this hot air travels from rack to CRAC, there are many opportunities for it to take a path of lesser resistance. Unfortunately, oftentimes these paths of lesser resistance are into another rack. This situation also arises because the rack is pulling in air in an attempt to cool the IT equipment. Not only does this create the same situation previously discussed, but it also leads to a situation of the hot air not returning to the CRAC, which leads to inefficiencies in the operation of the CRAC. If the incoming air to the CRAC does not meet the CRAC's minimum incoming air temperature setpoint, the electric strip heaters inside the CRAC will heat up the incoming air until the incoming temperature requirement is eventually met.

A much better arrangement for a data center is shown in Figure 39, in which the inlets of the rack are facing each other, and the outlets of racks are coordinated so that mixing of hot and cold air is not possible. In addition, perforated ceiling tiles are added in order to utilize the ceiling plenum both as a way to create a path of least resistance for the hot air and also as a path for the hot air to flow back to the CRAC. This hot/cold aisle arrangement meets the basic goal of segregating the cold and hot air.[81] Additional improvements, such as proper placement of perforated floor and ceiling tiles can be made to improve the airflow management once the hot/cold aisle arrangement is set-up.

4.2.3.3.1.2 Perforated Floor and Ceiling Tiles

Proper placement of perforated floor and ceiling tiles help ensure that segregated cold and hot air do not mix. The key to perforated floor tiles is to place them as close to the equipment air intakes as

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[81] (The Green Grid 2007)

possible to keep the cold air in the cold aisles only; indeed, poorly located perforated floor tiles are very common and erase almost all of the benefit of a hot/cold aisle layout.[82]

Two mistakes are common when it comes to perforated floor tile placement. The first is placing the perforated tile anywhere besides the cold aisle. One example of this situation, with the perforated floor tile, or "floor vent", placed too close to the CRAC unit, is shown in Figure 40. This situation creates a "short circuit", in which the cold air from the CRAC returns to the CRAC unit without cooling the IT equipment. As discussed previously, this returning cold air is reheated by the CRAC, which is a waste of electricity.

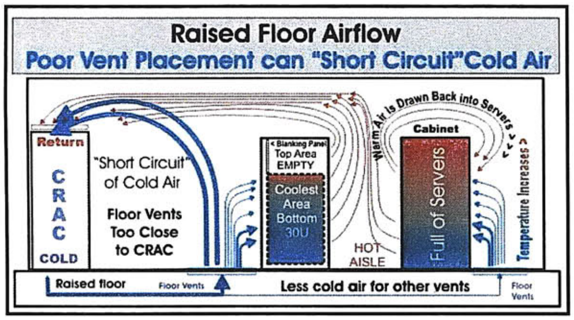

Figure 40: Example of poor placement of perforated floor tiles, or "floor vents", as it is referred to here[83]

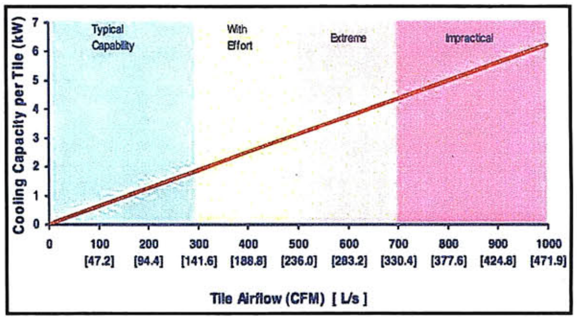

Figure 41: Diagram showing heat removal capacity of perforated floor tiles depending on the tile's airflow[84]

The second common mistake made with perforated floor tile is that the incorrect number of floor tiles is placed within the cold aisle. As shown in Figure 41, the perforated tile's airflow is directly related to how much heat it can remove from IT racks. Therefore, the perforated tiles should be places in such a way to remove the heat from the areas in which it is generated. For example, a rack that generates 1 kW of heat (consumes 1 kW of electricity) should have cold air flowing at 160 CFM in front of the rack. This airflow could be achieved either from one tile directly in front of the rack, or from two floor tiles in the cold aisle near the rack.

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[82] (Rasmussen, Avoidable Mistakes that Compromise Cooling Performance in Data Centers and Network Rooms 2008)

[83] (Neudorfer 2008)

[84] (Dunlap 2006)

To ensure that perforated tile placement is correct, many data center managers use computational fluid dynamics (CFD) to "tune" floor tile placement and the percent that the tiles are open.[85]

4.2.3.3.2 Computer Room Air Conditioning Modifications

The second important aspect of data center airflow management involves the computer room air conditioner (CRACs). While the floor layout is very important, approximately 25% of the total 36% potential savings in data center electricity is attributable to the CRAC improvements. These improvements include the placement of the CRACs in the data center, the use of chimneys to create closed loop airflow, and the coordination of all CRACs in the data center.[86]

4.2.3.3.2.1 Placement of CRACs in Data Center

CRAC units should be placed perpendicular to the racks, as shown in Figure 42. If there is a raised floor used to transport the cold air to the racks, then the CRACs should be located at the end of the hot aisles; while a non-raised floor data center should have the CRACs at the end of the cold aisle.[87]

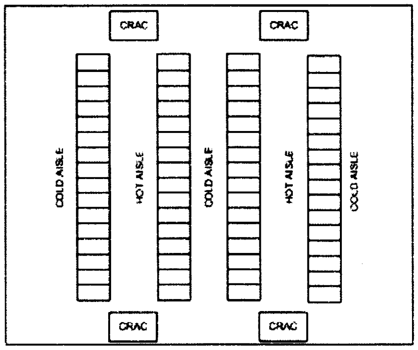

Figure 42: Rack arrangement showing layout of CRAC units in relation to the hot/cold aisle (top view). This diagram is for a raised floor data center.[88]

This alignment of the aisle with the CRACs ensures that the incoming air into the CRACs will be as warm as is possible, which will increase the efficiency and therefore the capacity of the CRACs. In addition, this aisle/CRAC alignment minimizes the opportunity for hot and cold air mixing, especially if perforated ceiling tiles are placed in the hot aisles. In addition to aisle/CRAC alignment, CRACs should be placed so the path between the CRAC and the cold aisle it is serving is minimized.

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[85] (The Green Grid 2007)

[86] (Rasmussen, Implementing Energy Efficient Data Centers 2006)

[87] (Dunlap 2006)

[88] (Dunlap 2006)

The shorter the distance from the CRAC to the cold aisle, the less the fan power that must be used to "push" the cold air from the CRAC to the racks.

4.2.3.3.2.2 CRAC Chimneys

Another method that can be used to form closed-loop airflow in a data center is to install a "chimney" from the CRAC to the ceiling plenum, as shown in Figure 43. The chimney should only be installed if heat generated from the racks is evacuated into a ceiling plenum. As with the placement of the CRAC, chimneys help ensure that the hottest air possible is returning to the CRAC, which in turn increases the capacity and efficiency of the CRAC.

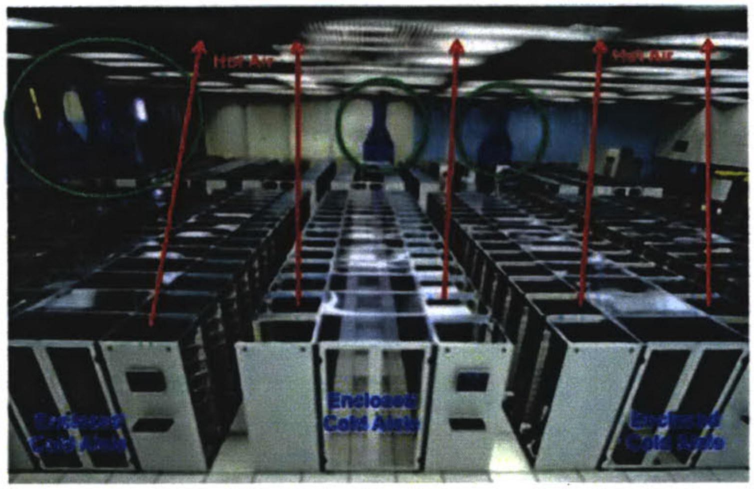

Figure 43: Example of CRAC chimneys, which are circled in green[89]

4.2.3.3.2.3 Coordinate Air Conditioners

Perhaps the easiest way to reduce electricity usage in a data center is to coordinate the CRACs. As shown in Figure 43, there are oftentimes several CRACs serving a data center. It is extremely common in such cases for two CRAC units to be wastefully fighting each other to control humidity, which occurs if the return air to the two CRAC units is at slightly different temperatures, if the calibrations of the two humidity sensors disagree, or if the CRAC units are set to different humidity settings.[90] The problem of CRAC fighting can be a 20-30% reduction in the efficiency of the

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[89] (Hirstius, Jarp and Nowak 2008)

[90] (Rasmussen, Avoidable Mistakes that Compromise Cooling Performance in Data Centers and Network Rooms 2008)

CRACs, and even worse can result in downtime due to insufficient cooling capacity.[91] There are four ways to correct CRAC fighting, as follows:[92]

1) Implement central humidity control.
2) Coordinate humidity control among the CRAC units.
3) Turn off one or more humidifiers in the CRACs.
4) Use deadband settings (when the deadband setting is set to +/-5% the problem will usually be corrected).

4.2.3.3.3 Rack Improvements

The third important aspect of data center airflow management involves the individual racks of IT equipment. While the floor layout is very important, approximately 8% of the total 51% potential savings in data center electricity is attributable to the rack improvements, which includes the use of cable cut-outs and blanking panels; the elimination of gaps between racks; and the minimization of obstructions in the airflow.[93]

4.2.3.3.3.1 Cable cutouts

One of the best examples of the need for behavior change in data centers is a requirement for cable cutouts. Even though measurements have shown that 50-80% of available cold air escapes prematurely through unsealed cable openings[94], many data centers still have large, unblocked holes for transporting cables. As shown in Figure 44, these holes allow cold air from the raised floor to flow in undesired locations, such as the hot aisle, instead of reaching the IT equipment. The result of this waste of cold air is additional requirements on the CRAC units, which uses additional electricity.

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[91] (Dunlap 2006)

[92] (Rasmussen, Avoidable Mistakes that Compromise Cooling Performance in Data Centers and Network Rooms 2008)

[93] (Rasmussen, Implementing Energy Efficient Data Centers 2006)

[94] (Dunlap 2006)

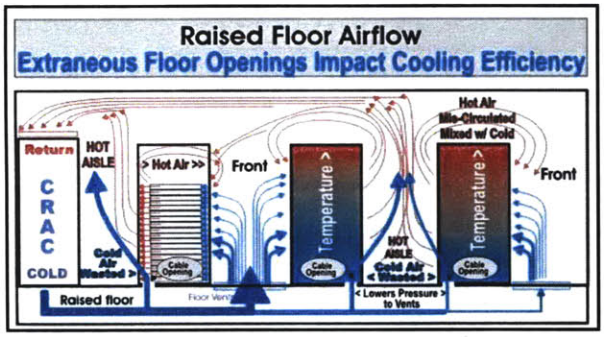

Figure 44: Example of poor placement of perforated floor tiles, or "floor vents", as it is referred to here[95]

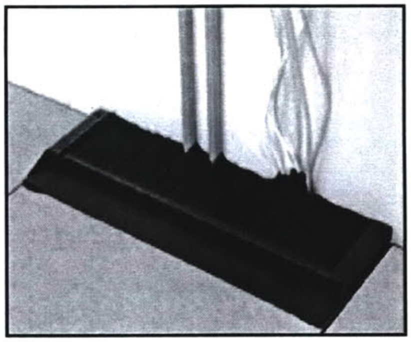

Figure 45: Example of a cable cutout that prevents the waste of cold air[96]

One way to prevent the waste of costly cold air is to use air containment, brush-type collars kits, as shown in Figure 45.[97] While this technology is well established, it is not fully deployed because data center managers oftentimes do not realize the impact that cable cut-outs have on the airflow and electricity usage. Another way to prevent the waste of costly cold air is to run all wires (networking and power) in the data center above the racks, which prevents the needs for cable cut-outs in floor tiles. This solution is easiest to implement when the data center is first designed and built, since moving the power and networking cables requires all IT equipment to be powered off.

4.2.3.3.3.2 Blanking Panels and Blanking Racks

Another common problem seen in data centers is missing blanking panels. Blanking panels are plastic pieces that match the width and height dimensions of a standard rack insert. The purpose of blanking panels is to eliminate a path for hot air generated from the rack to return to the front/input of the IT equipment, as shown in Figure 46. In addition to missing blanking panels, sometimes complete racks are missing from a line of data centers, which have the same re-circulation affect as a missing blanking panel, as shown in Figure 47.

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[95] (Neudorfer 2008)

[96] (The Green Grid 2009)

[97] (Neudorfer 2008)

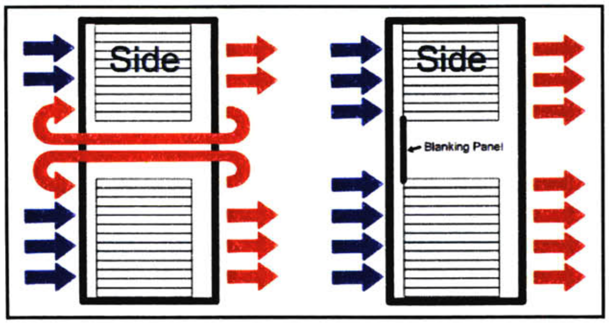

Figure 46: Example of rack without blanking panels (left) and with blanking panels (right)[98]

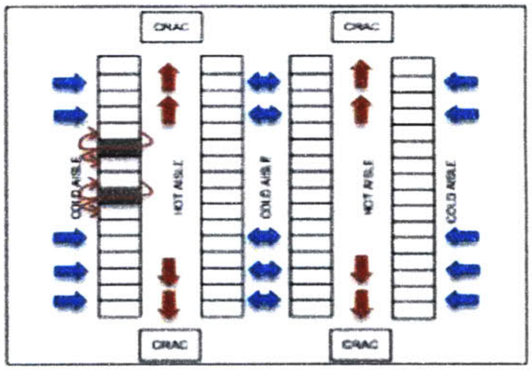

Figure 47: Missing racks in a row of racks allow hot air to re-circulate

If hot air is allowed to re-circulate and re-enter the IT equipment, an overheating of the equipment can occur. In addition, when the hot air generated by the IT equipment is re-circulated, it does not return to the CRAC, which lowers the CRAC's efficiency and cooling capacity. There are two reasons that blanking panels and blanking racks are not fully deployed, as follows:[99]

1) Data center managers believe they serve only aesthetic purposes.
2) They are difficult and time consuming to install (however, new snap-in blanking panels can help alleviate this problem).

Both of these factors are not technical in nature, and require behavior change and aligned incentives in order to ensure that blanking panels and blanking racks are used.

4.2.3.3.3.3 Minimize Obstructions to Proper Airflow

The presence of obstructions, as illustrated in Figure 48 and Figure 49, has a great influence on airflow uniformity.[100] Examples of raised floor obstructions are currently used network and power cable, and the lesser desired previously used network and power cables, trash, and dirt.

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[98] (Rasmussen, Implementing Energy Efficient Data Centers 2006)

[99] (Rasmussen, Improving Rack Cooling Performance Using Airflow Management Blanking Panels, Revision 3 2008)

[100] (VanGilder and Schmidt 2005)

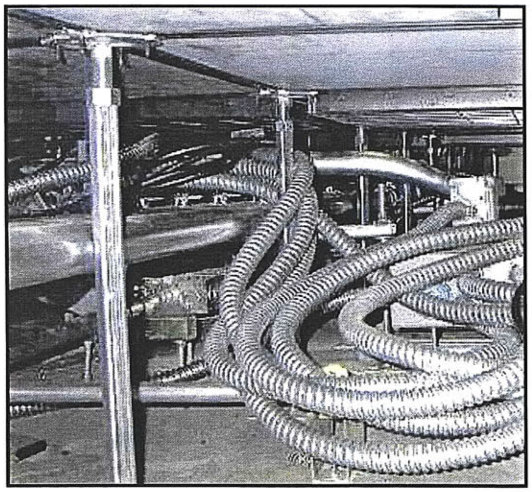

Figure 48: Power supplies acting as a raised floor obstruction[101]

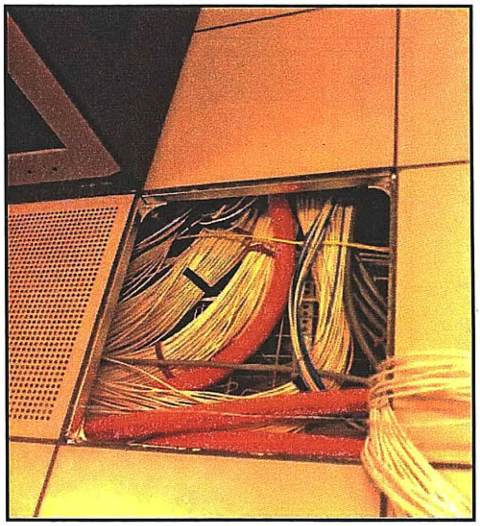

Figure 49: Network cabling acting as a raised floor obstruction[102]

One of the best ways to minimize raised floor obstructions is through frequent or interval cleaning and inspection. Another way to minimize raised floor obstructions is to run all wires (networking and power) in the data center above the racks. As stated earlier, this solution is easiest to implement when the data center is first designed and built, since moving the power and networking cables requires all IT equipment to be powered off.

4.2.4 Miscellaneous Equipment Energy Efficiency

As discussed in Section 2.2.2, miscellaneous equipment accounts for 2-3% of the total electricity consumed by data centers. Miscellaneous equipment is comprised of lighting, printers, copiers, and other equipment that may be inside the data center. Over time, most data center managers have tried to minimize the amount of non-essential equipment contained in data centers, since space is at a premium in many data centers, and since any non-essential equipment clutters the data center and obstructs efficiently airflow. Therefore, there are two ways to increase the efficiency of the miscellaneous equipment – remove it from the data center and focus on the efficiency of the data center lighting.

Lighting in data centers often provides an opportunity for electricity savings. Relatively low-cost timers and motion-activated lighting can reduce the amount of time that lights are on. The impact of

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[101] (Phelps 2009)

[102] (The Green Grid 2009)

lighting is double, since lights not only consume electricity, but also produce heat that must be removed by the heat removal equipment.[103]

4.3 Conceptual Framework

Since the focus of this thesis is to improve the electricity efficiency of existing data centers, best practices for the design of a new data center, as shown in Table 3, where not used in the pilot data center.

Table 3: Strategies for Reducing Electricity Consumption in New Data Centers

Data Center Component	Improvement Description	Capital Required[1]	Labor Required[1]	Behavior Change[1]	Savings[2]
Power Supply	Rightsizing	🟥	🟥	🟥	10-30%
Power Supply	Add on-site power generation to reduce or eliminate UPS	🟥	🟥	🟩	2-7%[3]
Heat Removal	Use in-rack water cooling	🟥	🟥	🟥	7-15%
Heat Removal	Use Cooling Economizer	🟥	🟥	🟩	4-15%

[1]Red = "Yes", Yellow = "In some Instances", Green = "No"

[2](Rasmussen, Implementing Energy Efficient Data Centers 2006)

[3]Assumed inefficiency of UPS was eliminated (Rasmussen, Electrical Efficiency Modeling of Data Centers 2006)

On the other hand, strategies that could be used to improve the electricity efficiency of existing data centers are shown in Table 4. Of the improvement opportunities listed, only "improve airflow management" and "install energy efficient lighting" were piloted. Improving the UPS was not an option because the data center did not utilize a UPS. However, the efficiency of the transformer utilized by the pilot data center was calculated for information purposes only. Consolidation, replacing obsolete equipment, and virtualization were not piloted because each of these methods requires capital, and because the IT equipment contained in the pilot data center was governed by existing contracts between Raytheon and the US Government. While Raytheon should pursue modifying existing contracts and putting emphasis of the IT equipment flexibility, it was out of the scope of this thesis. Managing the IT power consumption was not included in the pilot because proprietary agreements prevented the analysis of the power settings on the individual IT equipment contained in the data center.

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[103] (The Green Grid 2007)

Table 4: Strategies for Reducing Electricity Consumption of Existing Data Centers

Improvement Description	Piloted?	Capital Required[1]	Labor Required[1]	Behavior Change[1]	Savings[2]
Improved UPS	No	🟥	🟩	🟩	4-10%
Consolidation	No	🟥	🟥	🟥	unknown
Replace obsolete equipment	No	🟥	🟥	🟥	30-50%
Virtualization	No	🟥	🟩	🟥	10-40%
Manage power	No	🟩	🟩	🟥	
Improve airflow management	Yes	🟩	🟩	🟥	16-51%[3]
Install Energy Efficient Lighting	Yes	🟨	🟨	🟨	1-3%

[1] Red = "Yes", Yellow = "In some Instances", Green = "No"

[2] (Rasmussen, Implementing Energy Efficient Data Centers 2006)

[3] Sum of More Efficient Air Conditioner Architecture, More Efficient Floor Layout, Coordinate Air Conditioners, Locate Vented Floor Tiles Correctly, Reduce Gaps between racks/floors/walls, and Install Blanking Panels and Floor Grommets

Of the two remaining improvement opportunities ("improve airflow management" and "install energy efficient lighting"), a phased process was developed based on the difficulty and cost of implementing each improvement. As shown in Figure 50, there are short-term and medium/long term items within the improvement process. Because of time and budget constraints, only short-term, low-cost improvements were implemented in the pilot data center and the following data was analyzed to understand the impact of each improvement phase:

1) Airflow in front of racks
2) Air temperature at input and output of representative racks
3) Air temperature in plenum and near ceiling
4) Power load of CRACs
5) Instantaneous chilled water

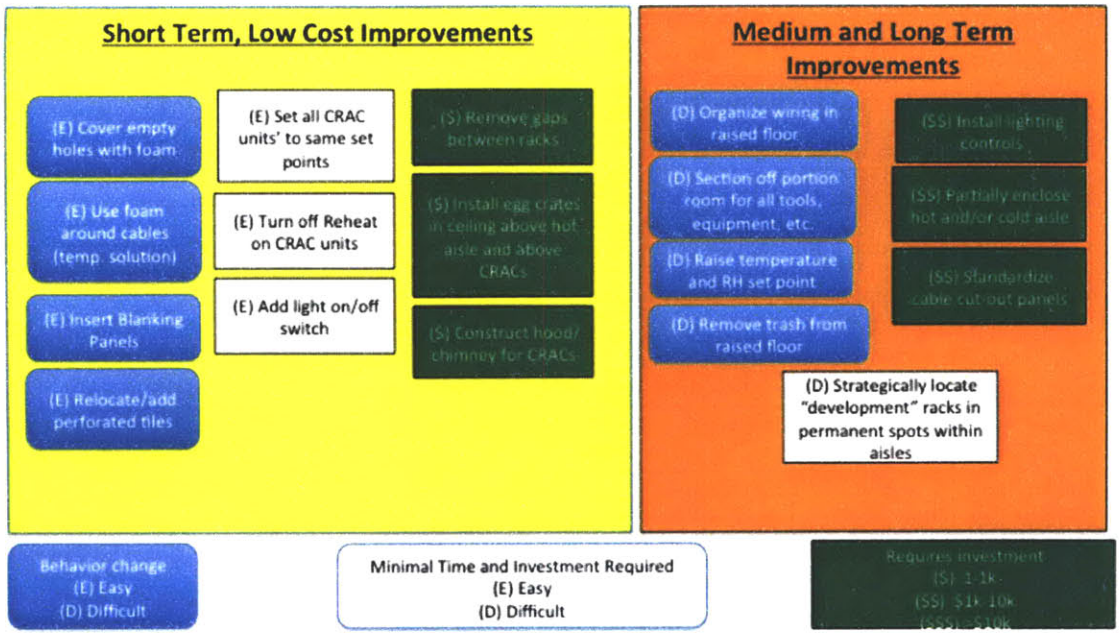

Figure 50: List of improvements for existing data centers

5 Results and Discussion of Piloted Improvement Process

5.1 Overview of Pilot Data Center

The pilot data center at the Raytheon Intelligence and Information Systems Garland site is approximately 1500 square feet, while the room could be about 1200 square feet if the space was optimally used. The size of the data center qualifies it as a "Localized Data Center", and a comparison of the actual and predicted characteristics is shown in Table 5.

Table 5: Comparison of typical and actual characteristics of the pilot data center

Typical System Characteristics[104]	Actual Characteristics of Pilot Data Center	Comparison
Under-floor or overhead air distribution systems and a few in-room CRAC units.	Under-Floor air distribution, and four in-room CRAC units	Same
CRAC units are more likely to be water cooled and have constant-speed fans and are thus relatively low efficiency	CRAC units utilize chilled water from central chilled water plant for cooling, and have constant-speed fans	Different
Operational staff is likely to be minimal, which makes it likely that equipment orientation and airflow management are not optimized	1-4 employees manage IT equipment staff, but are not responsible for energy efficiency	Same
Air temperature and humidity are tightly monitored	Air temperature and humidity is monitored 24/7 for out of range conditions	Same
Power and cooling redundancy reduce overall system efficiency	Two CRACs would probably meet requirements, four are present	Same

The data center is a test and development area, and some racks leave the room after they have been tested. Because of this testing environment, the number of racks varies from 45-55. There is an 18-inch raised floor and ceiling plenum in the room. Finally, as shown in Figure 51, there are four peripheral computer room air conditioning units (CRACs) in the room, which are connected to building's chilled-water system.

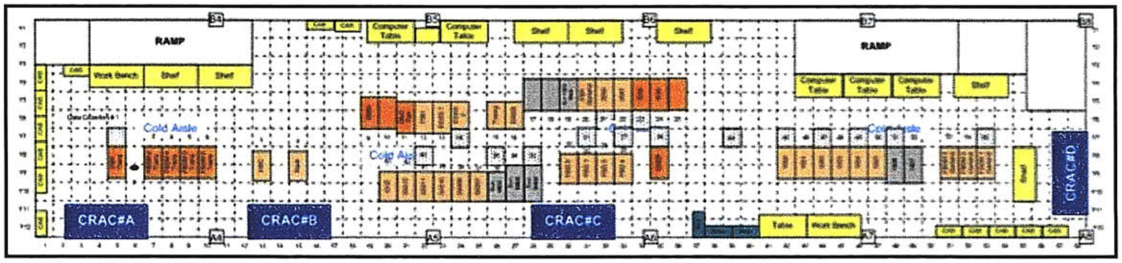

Figure 51: Diagram of Pilot Data Center

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[104] (Bailey, et al. 2007)

In addition, as shown in Figure 51, there are several areas of the room filled with non-essential equipment. For example, several computers, shelves, work benches, and cabinets are contained around the exterior of the room. The reason that the data center contains this non-essential equipment is because the room is a Sensitive Compartmented Information Facility (SCIF), and equipment is not easily taken in and out of the data center. For example, to avoid going through the security protocol each time a new rack needs to be assembled, the equipment required to assemble the rack is simply left in the room after assembly, so that it can be used the next time a rack is built. There is an additional, important aspect of the data center since it is a SCIF – it must be essentially self-sustaining. As the Physical Security Standards for Special Access Program Facilities states[105], "walls, floor and ceiling will be permanently constructed and attached to each other. To provide visual evidence of attempted entry, all construction, to include above the false ceiling and below a raised floor, must be done in such a manner as to provide visual evidence of unauthorized penetration." This requirement prevents the data center from using an air economizer; indeed, the only material that enters and exits the room is the chilled water from the building's chilled-water system.

5.2 Baseline Condition of Pilot Data Center

5.2.1 Power Delivery and IT Equipment Electrical Load

To understand the current state of the data center, baseline data was gathered. The first data that was collected was the electrical load of the room's IT equipment. As shown in Figure 52, the IT load was very consistent.

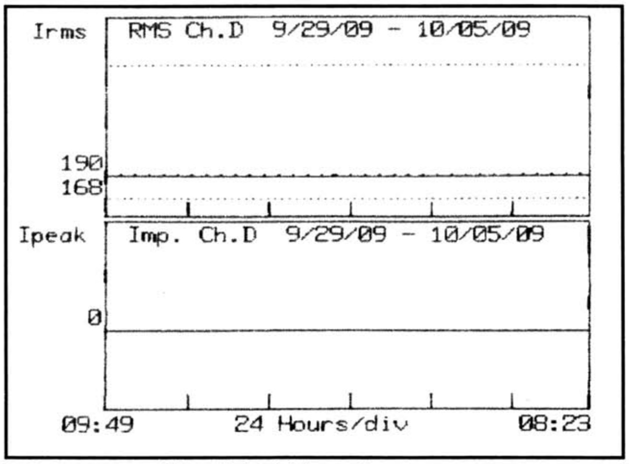

Figure 52: Current profile of the IT equipment over a one week period

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[105] (Joint Air Force - Army - Navy 2004)

The power for the IT equipment enters at 480V and is reduced to 220V by the power delivery unit (PDU). The 220V supply is fed directly to the electrical panels that supply electricity to the IT equipment. As shown in Table 6, the load is about 141 kW, and the transformer is extremely efficient (96.6%) at transforming the electricity from 480V to 220V.

Table 6: Electrical load of the IT equipment in the pilot data center

	480V					
	Min Current (Arms)	Max Current (Arms)	Avg Current (Arms)	Voltage	Average Load (kW)	Average Daily Load (kWh)
Phase A	171	198	184.5	279.2	52	1236
Phase B	147	174	160.5	279.2	45	1075
Phase C	168	190	179	279.2	50	1199
					146	3511
	220V					
	Min Current (Arms)	Max Current (Arms)	Avg Current (Arms)	Voltage	Average Load (kW)	Average Daily Load (kWh)
Phase A	396	418	407	120.15	49	1174
Phase B	352	366	359	120.15	43	1035
Phase C	398	422	410	120.15	49	1182
					141	3391
					Transformer Efficiency	96.6%

5.2.2 Heat Removal Equipment Electrical Load

The cooling system for the pilot data center consists of four CRACs, each fed by the building chilled-water system. One problem with determining the efficiency of the data center's overall cooling system is that the data center does not occupy the entire building. In fact, two other data centers are contained in the same building as the pilot data center. In addition, about one-half of the two-floor building is comprised of office space. To further complicate the calculation of electricity required to supply chilled water to the pilot data center, the building's chilled-water system is linked to another building's chilled-water system – both systems contain both a cooling tower and a chiller. Therefore, for the purpose of this pilot, a general efficiency value of 0.53 kWh/tonnage of cooling was used based on modern, large-scale chilled-water systems.[106] This value includes both the electricity required to produce the chilled water (cooling tower + chiller). Note that analysis of this value can be seen in Appendix V – Sensitivity of Chiller's Assumed Electricity Consumption.

The baseline condition of the pilot data center's cooling system is one of severe underutilization. Each of the four units is nominally rated at 422,000 BTU/hr or 124 kW of cooling, so there is almost

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[106] (The Green Grid 2009)

500 kW of cooling capacity in the data center. Since the IT load is 141 kW (reference Table 6), there is 3.5 times the amount of cooling capacity needed in the pilot data center. In addition to calculating the cooling capacity and comparing it to the IT-generated heat load, the load required to run the data center's CRAC units was monitored with a submeter. As shown in Figure 53, the load, which results from fan power and electric strip heaters (to reheat/humidify), is very cyclical. The average electrical load was calculated to be about 73 kW.

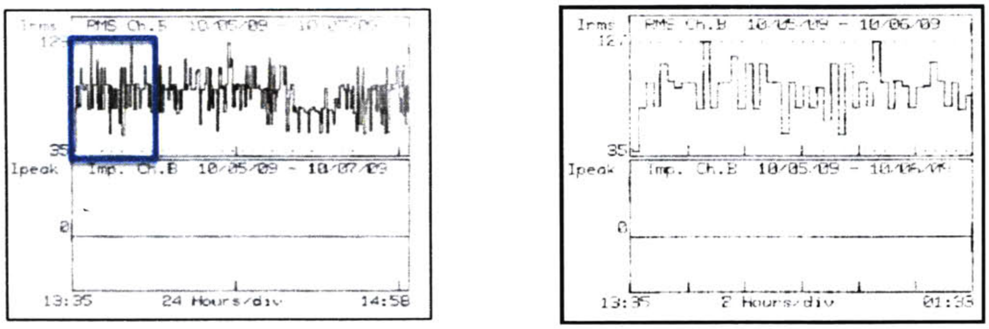

Figure 53: Current of the data center CRAC units on a three day (left) and one day (right) scale. Highlighted area in three day chart is area of one day chart.

This cyclical nature of the electrical load on the CRAC units indicates that the units are cycling between humidifying and dehumidifying functions. However, because this data center is closed to the outside atmosphere, there is no need to control the humidity. Since humidity is not a factor, the CRAC units were overcooling the room, which resulted in a need to reheat the air that cycled through the CRAC unit, only to remove the heat prior to sending the air into the raised floor. In addition to measuring the electricity required by the CRACs, the chilled water valves on the units were monitored, as shown in Table 7. The measurement showed that the chilled water required was 65 tons, which according to the calculations shown in Table 7, required 34.7 kW of electricity to produce. Therefore, the total electricity required for heat removal equipment is 108 kW.

Table 7: Chilled water usage and calculated electrical loads

CRAC	Chilled Water Valve (% opened)	Equivalent Chilled Water Tonnage[1]
A	55%	19
B	31%	11
C	54%	19
D	47%	16
	Total Tonnage of Chilled Water Required	**65**
Calculations	Electrical Load from CRAC Submeter	73 kW
	Electrical Load for chilled water	35kW
	Total electricity required for heat removal	**108kW**

[1]Each CRAC has a capacity of 35 tons

5.2.3 Miscellaneous Equipment Electrical Load

The only additional equipment that required electricity in the data center was the lighting. The data center contained 28 – 4 foot T8 lamp fixtures. Since each fixture containing four T8 bulbs requires 96 W of electricity, the total load for the lighting in the pilot data center was 2.7 kW. This electricity was required 24 hours a day, 7 days a week because there was no light switch present in the data center.

5.2.4 Summary of Baseline Electrical Load for Data Center

A summary of the baseline electrical load is shown in Table 8.

Table 8: Total baseline electrical load for the pilot data center

Component	Electrical Load (kW)	Daily Electricity Usage (kW/day)	Baseline %
Power Delivery System (loss from transformer)	5	120	2
IT Equipment	141	3384	55
CRAC	73	1752	28
Chilled Water	35	840	14
Lighting	2.7	65	1
Total	256.7	6161	100

In order to understand the electricity measurements and the data center efficiency, the power usage effectiveness (PUE), as illustrated in Figure 54, was calculated for the baseline condition of the pilot data center. A mathematically ideal PUE would be 1.0, in which 100% of the power from the utility is delivered to the IT equipment, with none being used by the infrastructure. Any value over 1.0 represents the "infrastructure tax" to run the data center.[107]

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[107] (The Green Grid 2009)

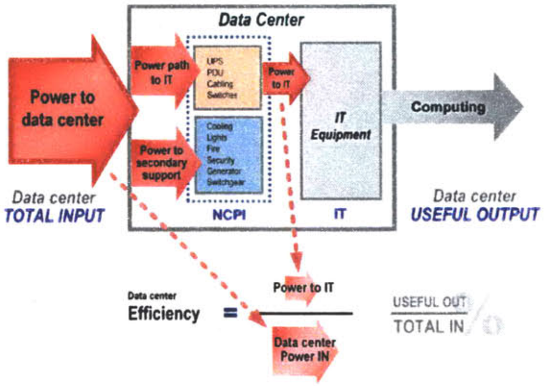

Figure 54: Detail of power consumption in a data center efficiency model[108]

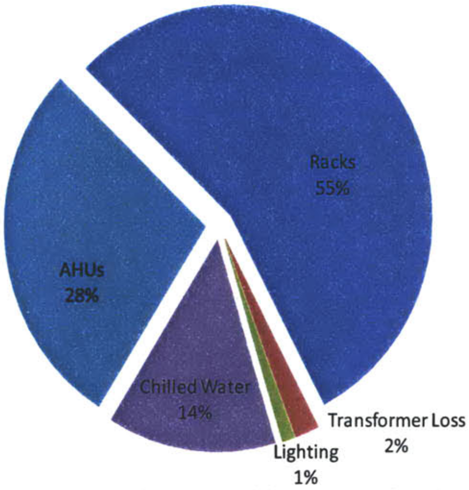

Figure 55: Baseline electricity usage for the pilot data center

The average PUE for industry data centers is 2.5, and data centers with the most efficient equipment and no over provisioning of capacity have been able to reach a PUE of 1.6.[109] The pilot data center, which has an electricity breakdown as shown in Figure 55, has a PUE of 1.82. However, there is a caveat to this value– there is no UPS in the pilot data center. The UPS in data centers can consume as much as 25% of the total electricity required for the data center.[110] In any case, the PUE provided a method to compare the effectiveness of the improvement process as it was implemented in the pilot data center. In addition to electrical load, airflow and air temperatures were measured in order to determine what affect the improvement process had on these critical aspects of the data center.

5.2.5 Baseline Airflow Measurements

Airflow is an important measurement because it indicates the amount of cold air that is reaching the IT Equipment from the CRAC units. In the case of a raised floor, airflow measurements can help a data center manager determine if the CRAC units are pressurizing the raised floor enough, too much, or optimally. As shown in Figure 56, the airflow is very dependent on whether a perforated floor tile is in front of the rack (note the location in Figure 51). However, even those racks that have perforated floor tiles directly in front of them do not exhibit the same airflow. This variation is due to the location in the room, as well as the size and number of holes on the perforated tile. The average value of the non-zero airflows for the baseline condition was 683 CFM.

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[108] (Rasmussen, Electrical Efficiency Modeling of Data Centers 2006)

[109] (Stansberry 2008)

[110] (The Green Grid 2007)

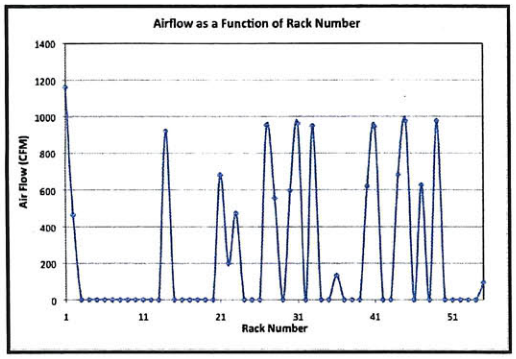

Figure 56: Variance in airflow in the pilot data center (baseline condition)

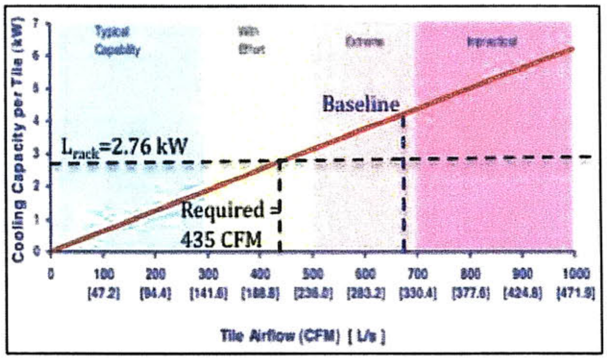

Figure 57: Comparison of actual and required airflow for pilot data center (baseline condition)

As shown in Figure 57, the baseline airflow (683 CFM) was much higher than required to remove the heat generated by the IT equipment (141 kW/51 racks, or an average of 2.76kW/rack) in the pilot data center. In fact, the airflow was 167% of the required airflow. This condition is not surprising, considering that the four CRACs serving the pilot data center had the capacity to provide 3.5 times the amount of cooling required according to the IT equipment load.

5.2.6 Baseline Air Temperature Measurements

In addition to measuring the airflow, the air temperature was measured in front of each rack, near the ceiling, and in both the ceiling plenum and the raised floor. Finally, air temperature was taken in several locations on a few racks in order to understand how efficiently the IT equipment was supplied cold air.

As shown in Figure 58, the air temperature in front of the racks was between 62 and 70.9°F; the average was 67.0°F and the standard deviation was 2.4°F. None of the air temperatures are close to the 80.6°F maximum that inlet air temperatures can be according to ASHRAE; indeed, most measurements are closer to the 64.4°F minimum specified by ASHRAE, and four data points are below the minimum.[111] This is an indication that the CRAC setpoints is too low, and electricity could be saved by raising the setpoints while still meeting the ASHRAE requirements.

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[111] (ASHRAE 2008)

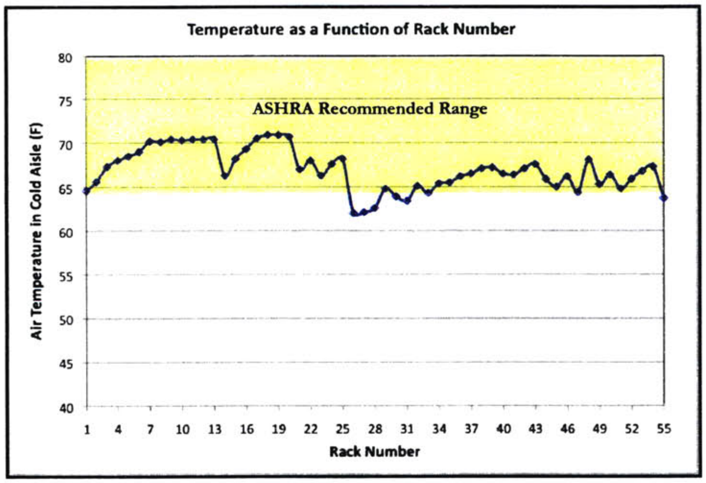

Figure 58: Variance in air temperature directly in front of each rack in the pilot data center (baseline condition).

As shown in Figure 59 and Figure 60, the air temperature in the hot aisles (outlet of the racks) is generally higher than the air temperature in the cold aisles (inlet of the racks). Also, the air temperature in the raised floor is 68-69°F in three of the four racks, while the air temperature in the raised floor in front of Rack 21 was 71°F, which could be an indication of blockage in between the CRAC output and the perforated tile in front of Rack 21. While the ceiling had a plenum, it was not used to evacuate air when the pilot began, as illustrated by the lower air temperature in the plenum than in room in some cases. This lack of evacuation of air from the hot aisle likely resulted in a "short circuit" and air mixing, which could have led to the higher temperatures as the distance from the ground increased in the cold aisle. This higher temperature near the top of racks could have also been due to missing blanking panels, which allowed air from the hot aisle to return to the cold air and re-enter the IT equipment.

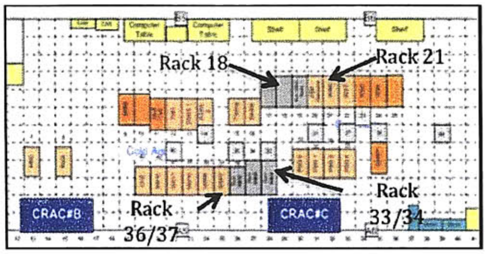

Figure 59: Diagram showing location of racks on which air temperatures were measured.

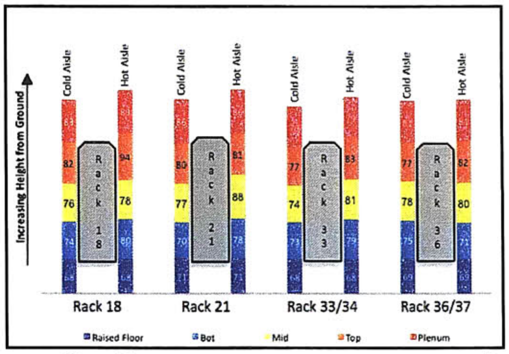

Figure 60: Air temperature measurements in the cold and hot aisle for selected racks (baseline condition). Note that Rack 21 and Rack 33 have perforated tiles in the cold aisle, while Rack 18 and Rack 36 do not.

The air temperature in the ceiling plenum, 6 inches below the ceiling (and above racks), and near two of the CRAC units was measured. As shown in Figure 61, the average air temperature 6 inches from the ceiling and above the racks varied from 78-84°F, with a standard deviation of various measurement points exhibiting a standard deviation up to 1.2°F. This relatively large standard deviation indicates that the hot and cold air was mixing. The temperature in the ceiling plenum varies from 73-78°F, and individual measurement points exhibited a standard deviation of about 0.3°F. Most concerning was the air temperature above CRAC B and C, which was 76°F and 82°F, respectively. This air temperature is lower than the air temperature in other parts of the room, as shown in Figure 61. This low air temperature, especially near CRAC B, indicates that the hot air generated by the IT equipment was not returning to the CRAC units, resulting in inefficient use of energy for both the CRAC units and the chilled water production.

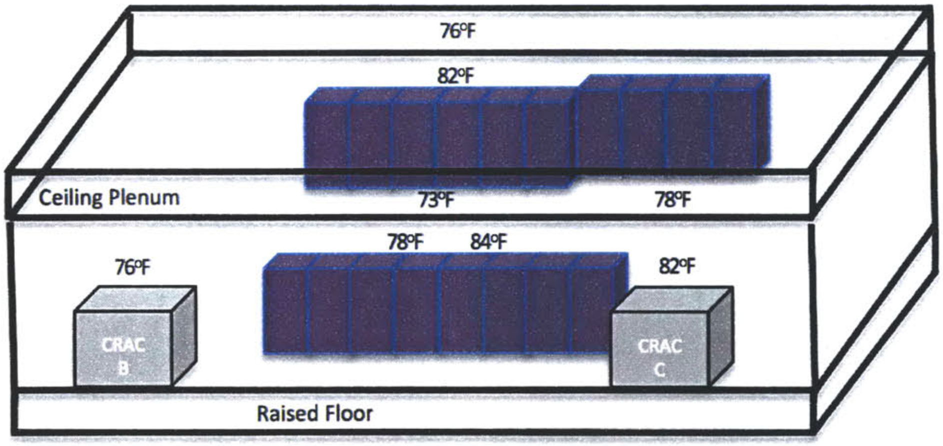

Figure 61: Diagram showing the average air temperature at various locations within the pilot data center (note only a portion of the data center is shown here). The average air temperature shown was derived from data taken over a one-week period.

5.2.7 Additional Visual Observations inside Pilot Data Center

Not only was electricity and air temperature documented, but a walkthrough of the data center was also completed in order to identify opportunities for improvement. The following observations were made during the walkthrough:

- Blanking panels within the racks were missing about 50% of the time (see Figure 62)
- Missing racks in the middle of rows existed in five locations
- Networking cables resulted in raised floor obstructions in several locations (see Figure 63)
- Perforated tiles were placed in two locations in which no rack existed (see Figure 64)
- Side and back doors were missing from several racks (see Figure 65)
- Cable cut-outs were much larger than required, and extra space was not blocked (see Figure 62 and Figure 63)

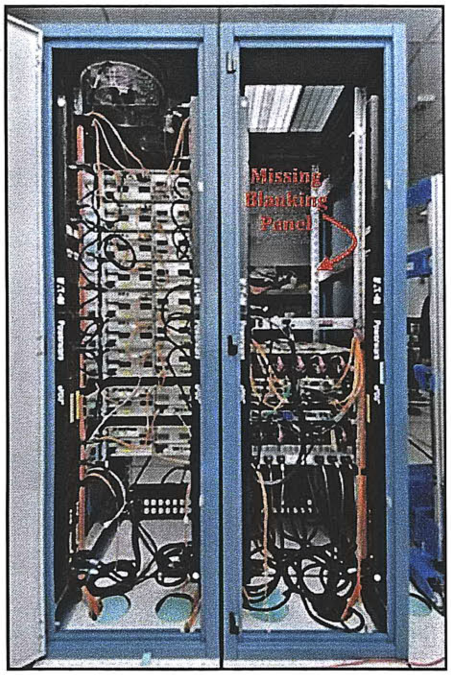

Figure 62: Picture showing missing blanking panels, missing doors, and unblocked cable cut-outs (baseline condition)

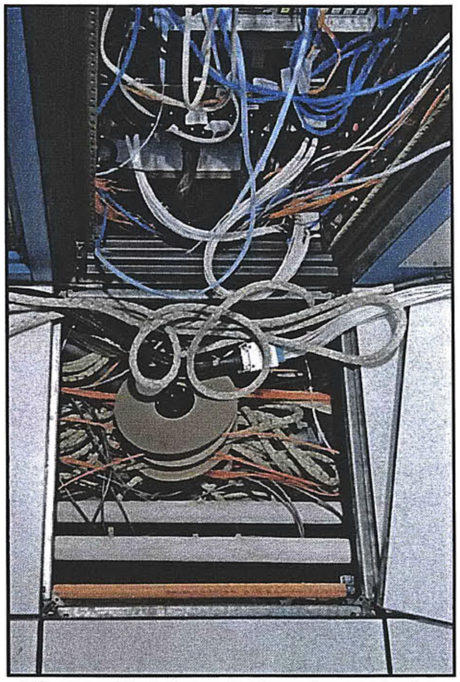

Figure 63: Picture showing missing unblocked cable cut-out and raised floor obstructions (baseline condition)

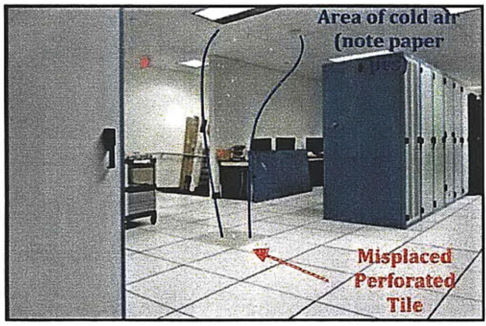

Figure 64: Picture showing randomly placed perforated tile blowing pieces of paper into the air (baseline condition)

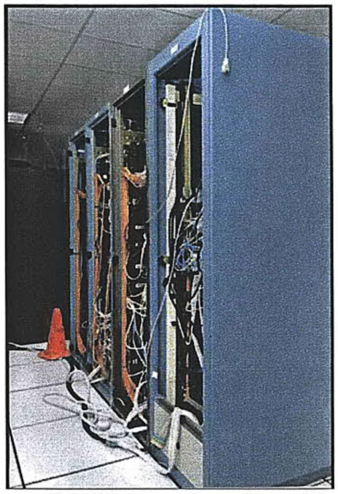

Figure 65: Picture showing missing doors from racks (baseline condition)

5.2.8 Summary of Baseline Condition

After reviewing the baseline data of the pilot data center, the issue, solution, and hypothetical result were developed, as shown in Table 9.

Table 9: Issues identified by data analysis in the pilot data center

Description	Root Cause	Solution	Hypothetical Result
24/7 Lighting	No lighting controls	Install light switch and occupancy sensors	Electricity savings
Air is reheat, humidified, and dehumidified unnecessarily	Default settings of CRACs were used, even though the room is a closed system	Disable reheat, humidify, and dehumidify settings on CRAC	Electricity savings
Heat Removal Equipment Overcapacity (3.5 times the IT equipment load)	Room was overdesigned	Turn off 1-2 CRACs	Increased efficiency of heat removal equipment, leading to electricity savings
Cold Air/Hot Air Mixing	Poor segregation of hot and cold aisle	Evacuate hot air into plenum	
Hot Air not returning to CRAC	Path hot air must take allows opportunities for mixing	Create vacuum from plenum to CRAC	
Missing blanking panels and racks	Incorrect behavior by data center manager	In short-term, correct mistake and train personnel. In long-term, align incentives and create standard operating procedures.	
Raised floor obstructions			
Poorly located Perforated Tiles			
Missing doors on racks (back and side)			
Unblocked cable cut-outs			

5.3 Implemented Improvements and their Affects on the Pilot Data Center

In order to understand how the efficiency of a data center could be improved, the short-term, low-cost improvement process developed from industry best practices, as shown in Figure 66, was implemented in the pilot data center. A detailed diagram showing the changes made can be found in Appendix IV – Changes made to the pilot data center.

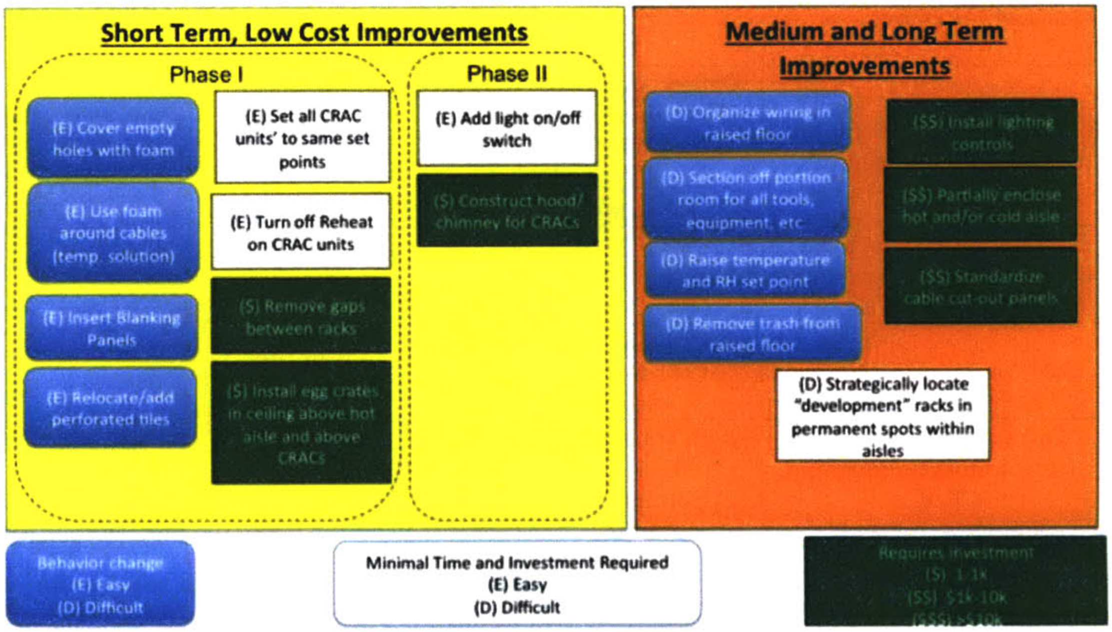

Figure 66: List of improvements for existing data centers

For logistical reason, the improvements were implemented in two phases; however, all the short-term, low-cost improvements shown in Figure 66 could be implemented at the same time in future data center improvement projects. As shown in Figure 67 and Figure 68, the changes made during this pilot were low-cost (~ $300), and were not difficult to complete.

Figure 67: Example of the changes (installation of egg crates above CRAC and blanking racks) made during Phase I and II

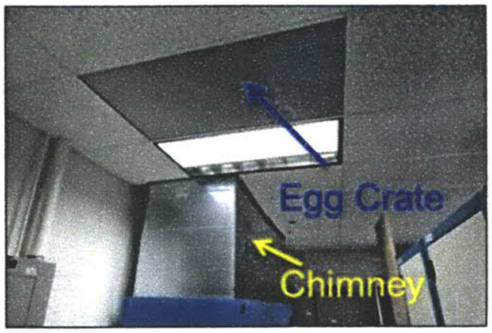

Figure 68: Example of the changes (installation of egg crates in hot aisles and chimneys on CRACs) made during Phase I and II

This phased approach allowed the team to differentiate the effects both the equipment (CRAC) and non-equipment changes had on the airflow, which will be discussed in the following sections. After all of the short-term, low-cost improvements were implemented, one CRAC unit (CRAC B) was turned off. The affects this shut down had on air temperatures, airflow, and electricity usage will be discussed in the following sections. Of particular interest was whether the changes and elimination of one CRAC would cause the IT equipment to overheat due to a lack of cold air from the raised floor.

5.3.1 Airflow Measurements

As shown in Figure 69 and Table 10, the airflow increased after the Phase I changes were implemented, and then returned to about the same value once the CRAC was turned off in Phase II. The 13.6% increase (93 CFM on average) in airflow observed after Phase I resulted because the problem of unplugged cable cut-outs and randomly placed perforated tiles was eliminated, stopping air from "short circuiting" - escaping from the raised floor prior to reaching the cold aisles. Even after one CRAC was turned off, the airflow only decreased by 4.4%, and still yielded an 8.6% increase from the baseline airflow. This is extremely strong evidence for how important it is to ensure perforated tiles are placed in the correct places and cable cut-outs are blocked.

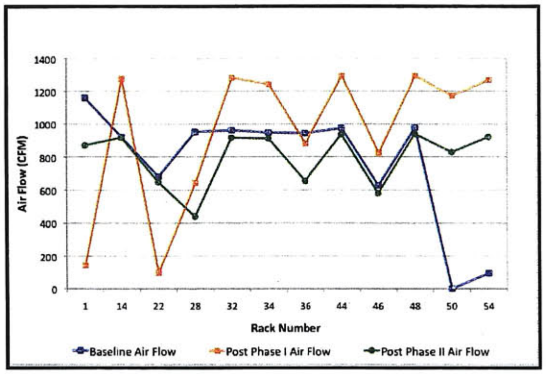

Figure 69: Variance in airflow in the pilot data center. Note that only the common perforated tiles are shown in this chart.

Table 10: Statistics for airflow per tile during different phases of the pilot process (non-zero, perforated tiles)

	Baseline	Post Phase I	Post Phase II
Avg Airflow (CFM)	683	776	742
Std Dev (CFM)	373	503	377
Min Airflow (CFM)	0	99	439
Max Airflow(CFM)	1161	1296	941

As shown in Figure 70, the airflow was much higher than it needs to be to remove the heat generated by the IT equipment (2.76kW per rack) in the pilot data center. Even after one CRAC was shut off, the airflow per perforated tile (average of 742 CFM) was much more than required. This indicates that "CRAC fighting" was occurring when all four CRACs were turned on, and there were probably small "cyclones" of cold air remaining in the raised floor rather than reaching the racks.

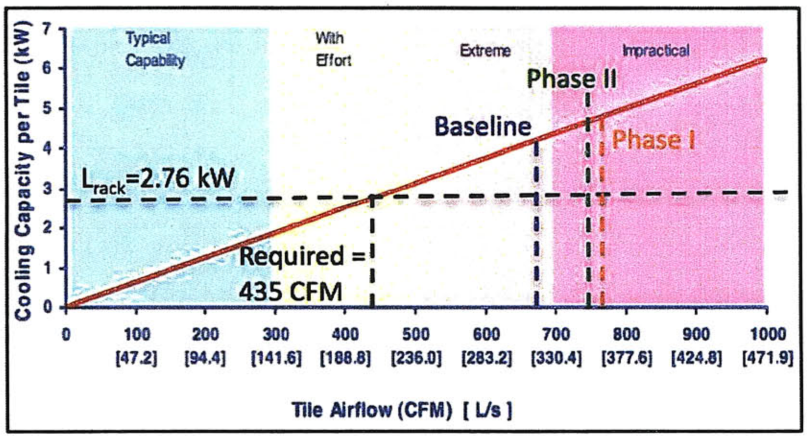

Figure 70: Comparison of actual and required airflow for pilot data center

5.3.2 Air Temperature Measurements

As shown in Figure 71, the air temperature in front of the racks was not adversely affected by the changes made to the data center. At no time did the air temperatures reach a temperature close to the 80.6°F maximum that inlet air temperatures can be according to ASHRAE; indeed, the average temperature in front of the rack was closer to the 64.4°F minimum specified by ASHRAE, as shown in Table 11.[112]

As shown in Figure 71, the air temperatures after all changes were implemented (Post Phase II) were lower than the baseline air temperatures at almost every point. It's quite remarkable that even after one entire CRAC unit was turned off (Post Phase II), the average temperature in the cold aisle was 1°F lower than the baseline condition. This is an indication that there was probably "CRAC fighting" occurring before the changes were made. The lower temperature is also an indication that the hot air from IT equipment is leaving the room via the ceiling plenum, rather than returning to the cold aisle and mixing with the cold air.

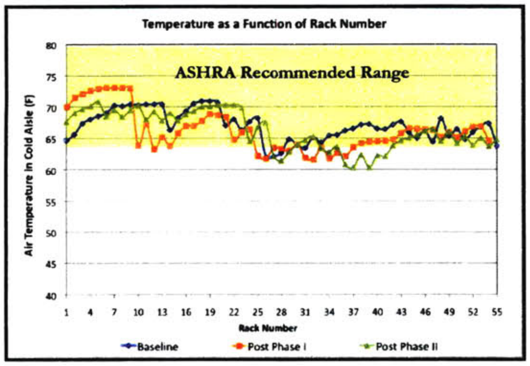

Figure 71: Comparison of air temperature during different phases of the pilot improvement process

Table 11: Statistics for air temperature in the cold aisle during different phases of the pilot process

	Baseline	Post Phase I	Post Phase II
Avg Temp (F)	67.0	65.0	66.1
Std Dev (F)	2.4	9.5	3.1
Min Temp (F)	62.0	61.6	60.3
Max Temp (F)	70.9	73.1	70.8

In addition to taking measurements in the cold aisle, air temperatures were taken in the ceiling plenum, six inches below the ceiling, and near two of the CRACs. As shown in Figure 72, there was a large increase in the air temperatures in the ceiling plenum. This large increase was due to the installation of perforated ceiling tiles, or "egg crates", which replaced the solid ceiling tiles that existed prior to the Phase I changes. These egg crates allowed hot air to flow from the data center to the ceiling plenum, and then flow from the plenum to the CRAC units. However, as indicated by the increase of the air temperature in the ceiling plenum above CRAC C, not all of the hot air was returning to the CRACs after the Phase I changes were implemented.

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[112] (ASHRAE 2008)

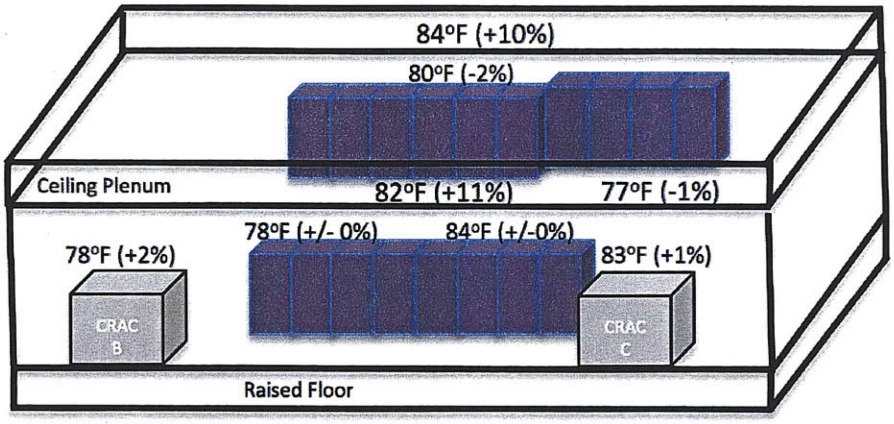

Figure 72: Diagram showing the average and change from baseline air temperature after the Phase I changes had been implemented within the pilot data center.

However, as shown in Figure 73-Figure 76, once the chimneys were installed onto the CRACs in Phase II, the temperature of the air returning to the CRACs increased to about the same temperatures observed in the ceiling plenum above the racks shown in Figure 72. This increase in hot return air resulted in an increase in the efficiency of the heat removal equipment, which will be discussed in section 5.3.3.

Also, as shown in Figure 73, mixing of hot and cold air that was evident above CRAC A was eliminated once the chimney was installed, while the mixing continued to occur above CRAC B as shown in Figure 74, since no chimney was installed. Another somewhat surprising result that was after CRAC B was turned off, the air temperatures in the raised floor, which were measured below racks near the applicable rack, decreased, as shown in Figure 74-Figure 76. This is a clear indication that CRAC B and CRAC C were involved in "CRAC fighting" prior to the elimination of CRAC B. In addition to illustrating "CRAC fighting", Figure 74 shows that a certain amount of suction of hot air from the plenum was occurring prior to the shut off CRAC B. This indicates that if installing chimneys is not possible, perforated ceiling tiles above CRACs help somewhat. However, as discussed previously, a benefit of the CRAC chimney is the elimination of mixing above the CRAC.

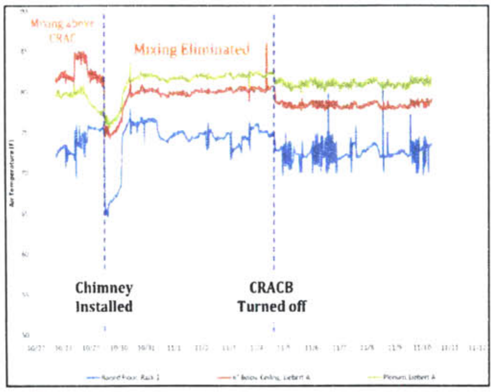

Figure 73: Air temperatures near CRAC A after Phase II changes were implemented

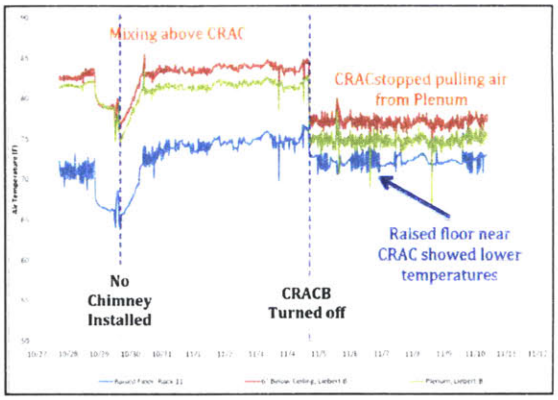

Figure 74: Air temperatures near CRAC B after Phase II changes were implemented

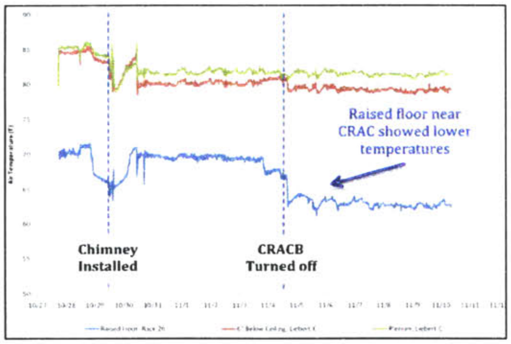

Figure 75: Air temperatures near CRAC C after Phase II changes were implemented

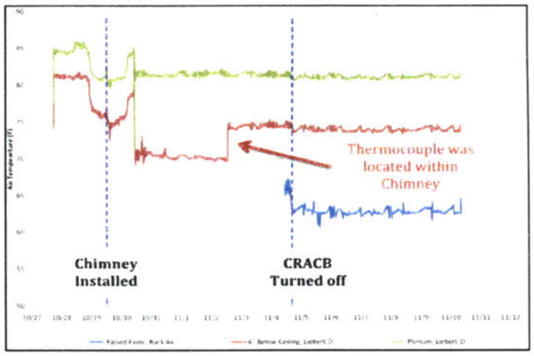

Figure 76: Air temperatures near CRAC D after Phase II changes were implemented

In addition to the perforated ceiling tiles, the blanking panels and blanking racks that were installed during Phase I probably helped to reduce the suction of hot air into the cold aisle, which in turn allowed more hot air to return to the CRAC units, leading to a higher efficiency. To understand the affect of the blanking panels and blanking racks, the air temperatures surrounding two racks were collected. As shown in Figure 78, the cold aisle exhibited a more consistent temperature range after the blanking rack (shown in Figure 77) was installed. For example, Rack 33, which originally had a blank space beside it, showed a range of air temperatures in the cold aisle of 73-77°F prior to the installation of the blanking rack. After the blanking rack was installed, the range of air temperatures in the cold aisle was 69-72°F. Both the overall temperatures and the range were reduced. In addition, the air temperatures in the hot aisle for Rack 33 increased from a range of 79-83°F to 77-

87°F after the blanking rack was installed. These changes are evidence of the reduction in mixing blanking racks can have on a data center. Rack 36, which never had an empty space beside it, showed less change from the baseline condition, as shown in Figure 78.

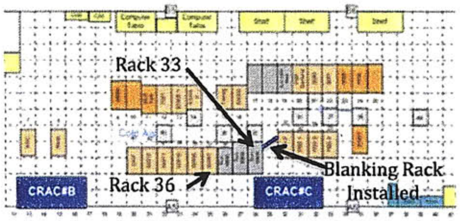

Figure 77: Diagram showing location of racks on which air temperatures were measured.

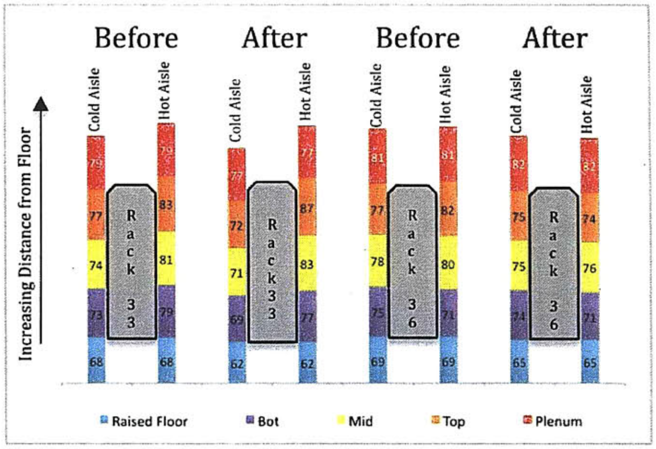

Figure 78: Air temperature measurements in the cold and hot aisle for selected racks. Note that Rack 33 has a perforated tile in the cold aisle, while Rack 36 does not.

5.3.3 Heat Removal Equipment Electrical Load

The electricity required by the heat removal equipment was altered in three ways:

1. Mixing of hot and cold air was drastically reduced, leading to an decrease in the amount of bulk cold air required, and thus a reduction in the electricity required by the CRAC units and also in the chilled water usage
2. Reheat, humidification, and dehumidification were disabled since the air contained in the data center was static
3. Hot air generated from the IT equipment was returned to the CRACs, leading to an increase in the operating efficiency of both the CRACs and the chilled water.

As shown in Figure 79 and Figure 80, a drastic reduction in the electricity took place during the pilot. In addition, the cyclical nature of the load was reduced so that the electrical load of the CRACs became almost constant. The total reduction in electricity required by the CRACs was 68% for the pilot data center.

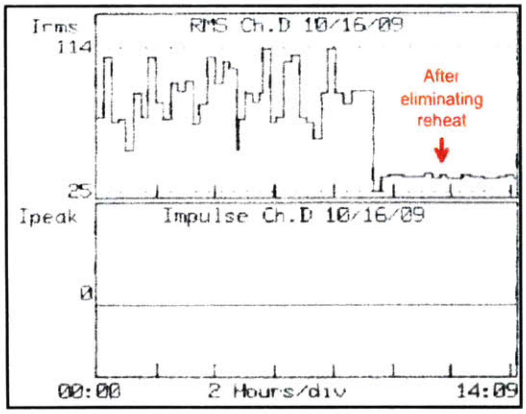

Figure 79: Current of the data center CRAC units before and after the reheat function was disabled on all four in room CRAC units.

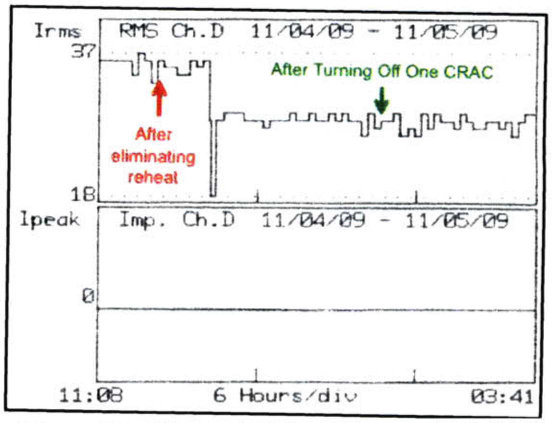

Figure 80: Current of the data center CRAC units before and after one of the units was turned off. In addition, dehumidification and humidification was turned off

As shown in Table 12, the electricity consumed by the CRACs changed significantly during the implementation of the improvement process. Since only three of the four CRAC units served the data center upon completion of the pilot, the cooling capacity was reduced 25% from 500kW to 372 kW. Even after shutting down one CRAC, there is still 2.6 times the amount of cooling capacity needed in the pilot data center, which is must closer to the n+1 condition desirable in critical data centers.

In addition to measuring the electricity required by the CRACs, the chilled water valves on the units were monitored, as shown in Table 13. The measurements showed that the chilled water required an average of 51.2 tons. Therefore, the electricity required by the chilled water system was reduced by 22% (27 kW versus the baseline value of 35 kW), and the total electricity required by the heat removal system is 50 kW/ton (a 54% reduction).

Table 12: Electricity consumed by CRACs during different stages of project

	Average Hourly Load (kW)	Average Daily Load (kWh)	Daily Reduction (kWh)	Change from Baseline	Annual Reduction (kWh)
Original AHU Fan Load	73	1,741	-	0%	-
Post Phase I, post reheat elimination	29	707	1,034	-59%	377,514
Post Phase II, post turning one off	23	556	1,186	-68%	432,820

Table 13: Chilled water usage and calculated electrical loads

CRAC	Chilled Water Valve (% opened on average after pilot was complete)	Equivalent Chilled Water Tonnage[1]
A	46%	16.1
B	0%	0
C	59%	20.7
D	41%	14.4
	Total Tonnage of Chilled Water Required	**51.2**
Calculations	Electrical Load from CRAC Submeter	23 kW
	Electrical Load for chilled water	27 kW
	Total electricity required for Heat Removal	50 kW
	Baseline Electricity Required for Heat Removal	**108 kW**

[1] Each CRAC has a capacity of 35 tons

5.3.4 Miscellaneous Equipment Electrical Load

A light switch was added next to the entrance of the data center so that the lights could be turned off when no one was present. The next step for the data center would be to add occupancy sensors to ensure that the lights were turned off when no one is present.

The data center contained 28 – 4 foot T8 lamp fixtures. Since each fixture requires 96 W of electricity, the baseline total load for the lighting – which was turned on 24 hours a day, 7 days a week – in the pilot data center was 2.7 kW. However, from interviews with the data center manager, the room is normally unoccupied 20 hours a day. It was assumed that the lights would be turned off during those hours, so that the electricity required for lighting the data center during use was 0.5 kW.

5.3.5 Summary of Electrical Load for Data Center

As shown in Figure 15, there was no change to the power delivery and IT equipment load, since changes such as consolidation and virtualization could not be completed due to budget and contractual constraints. Furthermore, no PUE existed in the pilot data center, and the transformer's efficiency was over 96%. Therefore, the only opportunities for savings were in the heat removal equipment and in the miscellaneous equipment. As discussed in the previous sections, the savings in electricity consumption by the CRAC and lighting was 50kW and 2.2 kW, respectively.

Table 14: Comparison of the baseline and post pilot electrical load for the data center

Component	Baseline Electrical Load (kW)	Baseline Daily Electricity Usage (kWh/day)	Post Pilot Electrical Load (kW)	Post Pilot Daily Electricity Usage (kWh/day)	Change from Baseline (%)
Power Delivery System (loss from transformer)	5	120	5	120	0
IT Equipment	141	3384	141	3384	0
CRAC	73	1752	23	552	-68.5
Lighting	2.7	65	0.5	12	-81.5
Chilled Water	35	840	27	648	-22.9
Total	257	6161	240.5	4716	-23.5

The improvements made a substantial improvement to the data center efficiency, as shown by comparing Figure 81 and Figure 82. Because of the 23% reduction in electricity consumption of the data center, the PUE of the pilot data center after the improvement process was implemented 1.39, a 23% increase from the baseline condition, which yielded a PUE of 1.82. As discussed earlier, the average PUE for industry data centers was found to be 2.5, and data centers with the most efficient equipment and no over provisioning of capacity have been able to reach a PUE of 1.6.[113] Even though the pilot data center had a PUE of 1.39 after the pilot was complete, the same caveat exists – there is no UPS in the pilot data center. The UPS in data centers can consume as much as 25% of the total electricity required for the data center.[114]

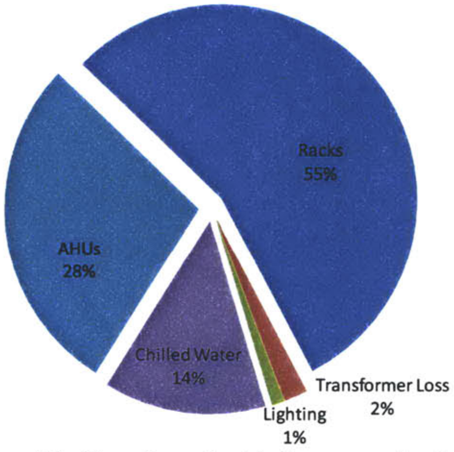

Figure 81: Baseline electricity usage for the pilot data center

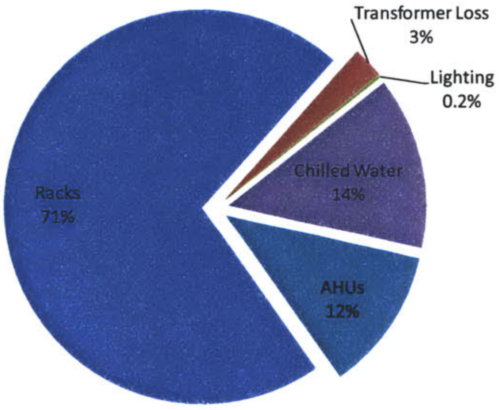

Figure 82: Post pilot electricity usage for the pilot data center

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[113] (Stansberry 2008)

[114] (The Green Grid 2007)

The improved PUE of the pilot data center further illustrates the improvement that occurred in the energy efficiency through simple, low-cost improvements. Additionally, when the electricity savings are translated into monetary savings, the results are staggering. As shown in Figure 83, the annual savings achieved in the pilot data center are approximately \$53.6k (recall only \$300 was used to implement all the changes in the pilot). The savings were calculated as follows:[115]

$$\text{Savings}_{\text{Annual}} = \text{Electric\_Savings}_{\text{Daily}} \times 365 \times \$0.106 \qquad (1)$$

Additional potential savings not achieved during the pilot were estimated by assuming that 20% of the electricity consumed by the racks could be eliminated if power management software was utilized (as discussed in Section 4.2.2.2). This assumption seems reasonable since the constant load of the building containing the data center shows a decrease in the constant load every December during the Raytheon holiday break, indicating that racks can be powered off. This additional savings, as shown in Figure 83, could increase the overall annual savings in the pilot data center to approximately \$83.9k.

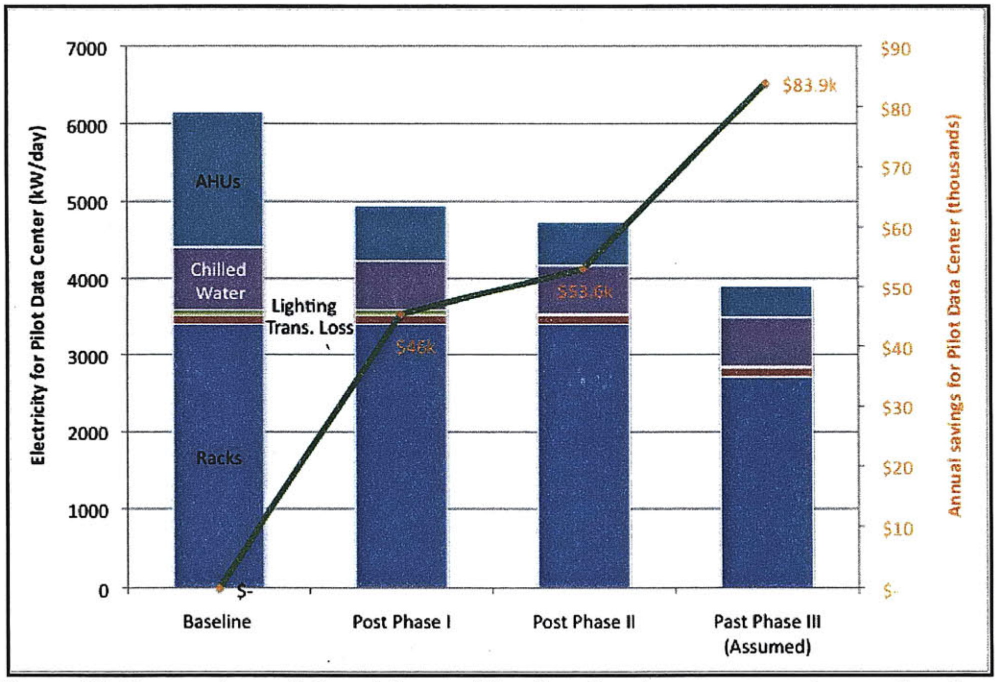

Figure 83: Comparison of electricity used by the pilot data center and annual savings achieved during different phases of the pilot program

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[115] Average 2008 electricity rate for commercial buildings: http://www.eia.doe/gov/cneaf/electricity/epm/table5_6.a.html

6 Recommendations to Maximize Return on Improvement Process

Most of the improvements made to the pilot data center are not technical, but behavioral in nature. While simply correcting the mistakes will increase the energy efficiency of data centers in the short-term, addressing the root cause in either the design phase or in the day-to-day management of the data center is essential to not only maintaining the changes, but also avoiding them in the first place. Two phases of a data center life cycle are key to the energy efficiency – the design phase and the use phase, as shown in Table 15. Both of these phases will be discussed in detail in the following sections.

Table 15: Issues identified by data analysis in the pilot data center

Description	Root Cause	Short-term Solution	Long-term Change Required
24/7 Lighting	No lighting controls	Install light switch and occupancy sensors	Implement lighting controls in DESIGN PHASE
Air is reheat, humidified, and dehumidified unnecessarily	Default settings of CRACs were used, even though the room is a closed system	Disable reheat, humidify, and dehumidify settings on CRAC	Right size during the DESIGN PHASE
Heat Removal Equipment Overcapacity (3.5 times the IT equipment load)	Room was overdesigned	Turn off 1-2 CRACs	Right size during the DESIGN PHASE
Cold Air/Hot Air Mixing	Poor segregation of hot and cold aisle	Evacuate hot air into plenum	Improve DESIGN PHASE; Intensify DATA CENTER MANAGEMENT
Hot Air not returning to CRAC	Path hot air must take allows opportunities for mixing	Create vacuum from plenum to CRAC	
Missing blanking panels and racks	Incorrect behavior by data center manager	Install blanking panels	Intensify DATA CENTER MANAGEMENT
Raised floor obstructions		Remove obstructions	
Poorly located Perforated Tiles		Move perforated tiles	
Missing doors on racks (back and side)		Install doors on racks	
Unblocked cable cut-outs		Use foam or special cable cut-out tiles	

6.1.1 Correcting Design Phase Mistakes through Management Techniques

As discussed in section 4.2.1.1, rightsizing during the design of a data center can reduce the electricity usage of a data center by up to 30%. As shown in the pilot data center, the heat removal system was overdesigned such that one entire CRAC unit could be turned off. In fact, turning one of the four CRACs off actually decreased the temperature of the cold air getting to the IT equipment and increased the airflow, both desired outcomes. So, why are data center overdesigned, and what are the keys to rightsizing?

In the case of the pilot data center, the room was designed to meet the maximum electrical requirements of the IT equipment. This is a very common, because the cost of downtime due to a data center has soared in recent years.[116] To ensure that the data center experiences no downtime, facility designers simply design the data center to the worst-case scenario – all pieces of IT equipment consuming the maximum amount of electricity possible. Two solutions exist to correct overdesigning – rightsizing with provisions and integrated design teams.

Rightsizing should be performed as discussed in section 4.2.1.1; however, provisions, such as temporary heat removal equipment should be purchased to avoid under capacity, and more importantly, to put data center managers at ease. To ensure that rightsizing occurs correctly, the IT and facilities departments must be better integrated. As shown in Figure 84, the power of IT equipment are the top two concerns among data center managers, yet there is an inherent lack of communication between the IT and facilities departments of most companies. The result is that most data centers design and build or upgrade projects are painful, lengthy, and costly.[117]

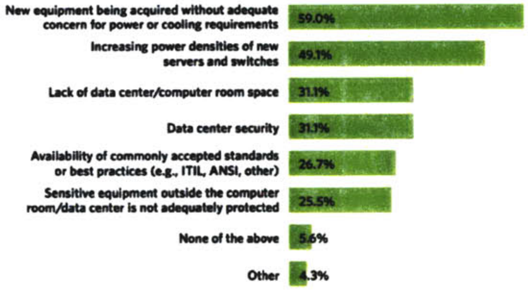

Figure 84: Survey results of what is keeping data centers managers "up at night"[118]

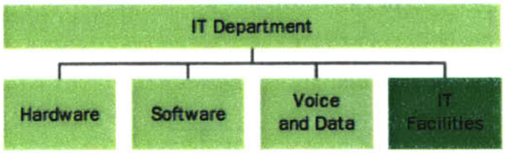

Figure 85: Example of Staff Alignment for Energy Efficiency[119]

In the case of the pilot data center, the room was designed and built by the facilities organization; while the day-to-day activities, including purchasing and setting up IT equipment, is managed by the

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[116] (Stansberry 2008)

[117] (The Green Grid 2007)

[118] (Sneider 2005)

[119] (The Green Grid 2007)

IIS program who uses the servers, data storage, and network equipment contained in the data center. Facilities involvement after the initial design and build is minimum, and includes periodic maintenance of the heat removal equipment and responding to tickets that specify an undesired condition, such as "the room is too hot." In addition, the facilities organization manages the payment of the utility bills; however, they are not incentivized to reduce the electricity consumed because any savings simply affects the accounting bottom line and is not provided to the facilities department for additional projects. Those who manage the data center have no visibility of the electricity consumed by the data center, and also are not incentivized to reduce the electricity consumed; rather, their performance is based on the amount of downtime and the speed at which they can get new IT equipment running. To remedy this situation, organizations and the incentive structures must be better aligned to ensure that energy efficiency is important to the data center design team.

An example of an alignment that is conducive to energy efficiency considerations is shown in Figure 85, in which an IT Facilities group reports directly to the Chief Information Officer (CIO) and is responsible for the initial design of data centers. While organizational structure puts emphasis on energy efficiency, incentive and accountability must be set-up to ensure there is follow through by the data center design team. One barrier that must be overcome in order to implement accountability is lack of visibility. For many organizations, including the case of the pilot data center, only one bill for the entire site is received from the utility company for electricity. Most of the time, the bill is received not by the IT department, but by the finance or facilities department. After checking the bill quickly for obvious errors, and in seldom cases comparing the bill to the previous month or previous year, the finance or facilities department simply pays the bill to ensure that there is no disruption to the power into the plant. Indeed, in a 2008 survey on data centers' purchasing intentions, 36% of the respondents did not even know whether their utility power costs had increased or decreased since 2007.[120]

Therefore, to set up accountability and the correct incentive structure, submetering of high-energy users, such as data centers, should be implemented to whatever extent possible. The submetering can be temporary, as it was with the pilot data center, or permanent. The electricity data should be used to charge the high-energy users for their portion of the electricity bill and to set-up incentives, such as performance management metrics that affect future salaries and bonuses, to make sure that those with the ability to create change are motivated to do so. If it is too difficult because of existing

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[120] (Stansberry 2008)

customer contracts and multiple customers to separate the bill and charge end users, then at least goals should be set for energy efficiency targets for high-energy users such as data centers. For example, a 25% increase in PUE could be required annually and listed as a performance management metric of both the IT and facilities leadership team. This would not only incentivize the IT and facilities departments to design data centers using techniques such as rightsizing and virtualization, but it would also drive a culture of continuous improvement year-to-year, forcing IT and facilities departments to collaborate and search for consolidation techniques and purchase the most energy efficient equipment available for new contracts. Unfortunately, the importance of purchasing the most energy efficient IT equipment is often overlooked. It is unfortunate because the three-year cost of powering and cooling servers is currently 1.5 times the capital expense of purchasing the server hardware.[121]

In summary, in order to increase the energy efficiency of a data center over the life of the equipment, the IT and facilities departments should be better integrated through organizational alignment. In addition, incentives should drive accountability and a culture of continuous improvement year-to-year to ensure that right decisions are made not only during the design of the new data centers, but also during the purchasing of new equipment for existing data centers.

6.1.2 Correcting Use Phase Mistakes through Employee Engagement

While the design of a data center has a substantial impact on its lifetime electricity consumption, the day-to-day management is the most important factor when it comes to the efficiency of the heat removal system, which can account for as much as 50% of the total electricity consumed by a data center.

As discussed in the previous section, those who manage the data centers at IIS have no visibility of the electricity consumed by the data center and are not incentivized to reduce the electricity consumed. Rather, their performance is based on the amount of downtime and the speed at which they can get new IT equipment running. However, when the project team – consisting of only facilities personnel – chose the pilot data center, the personnel responsible for the room showed a remarkable amount of engagement during the improvement process. The purpose of this section is to discuss how a high level of employee engagement was achieved, and how the process can be replicated in other data centers.

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[121] (Stansberry 2008)

Five aspects played a key role in achieving employee engagement of the program personnel who "owned" the pilot data center, as follows:

1. Awareness
2. Commitment
3. Action
4. Feedback
5. Competition

The first step of engaging the pilot data center's manager was to raise awareness of data center energy efficiency by discussing the current state of the pilot data center. In addition, the team provided the data center manager the total monthly and annual bill for electricity at the Garland IIS site, and how the electricity bill affected the overhead cost and therefore the ability of IIS to win new contracts. In addition, the environmental impact of Garland's energy usage was discussed. In addition, benefits of improving the energy efficiency of the pilot data center, such as additional capacity in the data center and increased reliability/redundancy of the heat removal equipment, were discussed. Finally, rather than simply stating what was wrong with the pilot data center, the team – including facilities and the data center manager – walked through the data center and discussed possible improvement opportunities. By making the data center manager part of the team, it was much easier to make improvements once the pilot began. Prior to making any changes, the plan was discussed with the data center manager in order to cultivate an extremely inclusive team environment.

The second step of achieving employee engagement was gaining public commitment. Research suggests that a public commitment (as opposed to a one-on-one or private commitment) leads to a reduction in energy usage. For example, homes that made a commitment to decreasing their energy use reduced their usage 10-20%, whereas a control group that made only a private commitment showed no change in their energy usage.[122] In the case of the pilot data center, the team gained public commitment by holding a meeting between facilities management, the data center manager, and the data center manager's boss. In the meeting, proposed changes were reviewed, and the team asked for commitment. One common flaw when achieving commitment is to pressure people in to commitment, which research suggests does not work.[123] To avoid applying pressure for the pilot data center, the team created a very informal environment when asking for public commitment.

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[122] (Pallak, Cook and Sullivan 1980)

[123] (McKenzie-Mohr and Smith 1999)

The third step of achieving employee engagement was encouraging the data center manager to take action, rather than directing facilities personnel to make agreed upon changes. For example, rather than simply installing the blanking panels and blanking racks, the team provided the data center manager with a white paper on the importance of blanking panels, and asked what assistance would be helpful in ensuring blanking panels were installed in the short and long-term. One day after the discussion took place, all missing blanking panels had been installed by the data center personnel.

In order to continue cultivating employee engagement, feedback was provided to the data center manager and his team. Feedback is essential in order to sustain change. In one study, simply providing feedback increased recycling by more than 25%.[124] However, when feedback was combined with public commitment, the resulting increase in recycling was even higher - 40%.[125] To provide feedback during the pilot, the electricity consumed by the CRACs were provided before and after the reheat function had been disabled, illustrating the impact that the project was having on the data center's electricity consumption, the building's electricity consumption, and the overall Garland site's electricity consumption.

Finally, the last step of achieving employee engagement is to create a competitive environment. Most companies and sites have multiple data centers. While the team was unable to create a comprehensive competitive environment in only six months, one measure that could be used to create a competitive environment among data center managers is the power usage effectiveness (PUE). Not only could the PUE be used to create competition, but it also allows a way to prioritize the implementation of the improvement process across multiple data centers.

6.2 Suggested Implementation Plan for Data Centers

Oftentimes it is difficult in large organization to roll-out large initiatives, even if there is evidence vis-à-vis a pilot that illustrates potential results. To increase the chances of a successful roll-out of the piloted improvement process, Raytheon (and other organizations) should observe why the Garland team was successful, as illustrated in Figure 16.

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[124] (Deleon and Fuqua 1995)

[125] (Deleon and Fuqua 1995)

Table 16: Key questions and answers that highlight a successful implementation process

Key Question[126]	Answer
Why was the team successful in Garland?	1) Facilities/IT leadership buy-in 2) Clear leader for implementation 3) Employee engagement 4) Team was empowered to make decisions and implement changes
What is similar between the Garland site and other sites/companies where the pilot will be implemented?	1) Increasing data center energy efficiency can be a compelling and competitively significant goal that every employee can relate to viscerally 2) Data centers are owned jointly by facilities, IT, and program support 3) Electricity is paid for by facilities
What is different between the Garland site and other site/companies where the pilot will be implemented?	1) Data center attributes like age, layout, number/site, etc vary from site to site 2) Emphasis on energy conservation

From the answers to the above questions, a three step process was developed that could be followed to implement the pilot process in both Raytheon and also other companies to ensure that the results achieved during the pilot could be replicated:

1) Gain buy-in and commitment from leadership for data center improvements
2) Create Rapid Results Teams (RRTs) to implement the improvement process
3) Allow feedback and increased knowledge to be shared amongst the RRTs

Each of these steps will be discussed in more detail in the following sections.

6.2.1 Gain buy-in and commitment from leadership for data center improvements

When reflecting on why the team was so successful in implementing the pilot process, the first thing that comes to mind is leadership buy-in. Because the leadership team from Facilities, IT, and the Program agreed upon the need to improve the energy efficiency of data centers, the team was empowered to make changes quickly, without repeatedly asking for permission. The method for achieving leadership buy-in was to communicate the importance of data center energy efficiency through anecdotes and relatable information. As shown in Figure 86, prior to the start of the project, the leadership was shown the extent to which data centers were affecting their operations cost. To make the data relatable, a car, in this case the Nissan Versa was used to illustrate how much money was spent daily on electricity for Garland data centers. In addition, once the pilot was complete, the information shown in Figure 87 was provided to the leadership team. The savings information not only recognized the team's success, but also provided the leadership team with a strong incentive –

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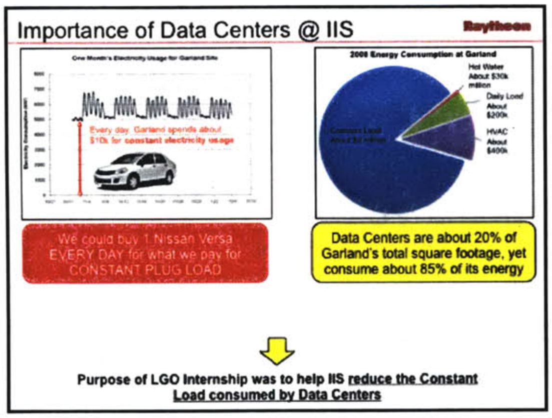
[126] (Beers November-December 1996)

almost $500k in savings – to continue the implementation of the data center energy efficiency process.

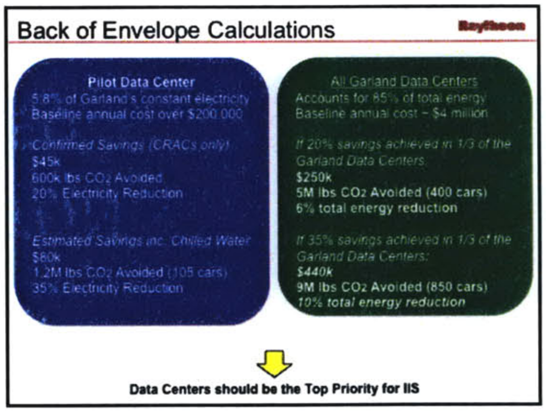

Importance of Data Centers @ IIS

We could buy 1 Nissan Versa EVERY DAY for what we pay for CONSTANT PLUG LOAD

Data Centers are about 20% of Garland's total square footage, yet consume about 85% of its energy

Purpose of LGO Internship was to help IIS reduce the Constant Load consumed by Data Centers

Figure 86: Example of slide shown to Facility Leadership to gain buy-in of importance of data centers


Back of Envelope Calculations

Pilot Data Center
5.8% of Garland's constant electricity
Baseline annual cost over $200,000

Confirmed Savings (CRACs only)
$45k
600k lbs CO2 Avoided
20% Electricity Reduction

Estimated Savings inc. Chilled Water
$60k
1.2M lbs CO2 Avoided (105 cars)
35% Electricity Reduction

All Garland Data Centers
Accounts for 85% of total energy
Baseline annual cost – $4 million

If 20% savings achieved in 1/3 of the Garland Data Centers:
$250k
5M lbs CO2 Avoided (400 cars)
6% total energy reduction

If 35% savings achieved in 1/3 of the Garland Data Centers:
$440k
9M lbs CO2 Avoided (850 cars)
10% total energy reduction

Data Centers should be the Top Priority for IIS

Figure 87: Example of slide show to Facility Leadership to keep momentum of data center projects

6.2.2 Create Rapid Results Teams to implement the improvement process

Generally, two organizations – Facilities and IT – are responsible for data centers. Therefore, the leadership of these two organizations should create and empower Rapid Result Teams (RRTs), comprised of facilities and IT personnel, to implement the data center improvement process. The first deliverable assigned to the RRT should be the creation of a prioritized list of data centers to improve. Next, the leadership of Facilities and IT should assign each data center both a specific RRT and a specific date for full implementation of the data center improvement process. Setting aggressive goals for implementation will empower the teams, communicate the importance of the initiative to the entire organization, and provide savings rapidly. If RRTs are results oriented, vertical, and fast, maximum benefits will result from their existence.[127]

6.2.3 Allow feedback and increased knowledge to be shared amongst the RRTs

One very important capability required to create a high performing, high velocity organization is knowledge sharing.[128] In the case of RRTs, the best approach to share information and further refine the improvement process is through a Lean tool called jishuken (pronounced "jee-shoe-ken"). Jishuken, an example of which is shown in Figure 88, is the process of first asking RRTs from different sites to perfect data center improvement processes specific to the data centers at their site.

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[127] (Matta and Ashkenas Septmeber 2003)

[128] (Spear 2009)

Next, RRTs visit other sites and work with local data center RRTs to further increase the energy efficiency of each site's data centers.

Figure 88: Jishuken Dynamic[129]

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[129] (Spear 2009)

7 Conclusion

The impact of the low-cost, systematic approach for increasing the energy efficiency of data centers was a 23% reduction in electricity consumption, leading to annual savings of over $53k. If other low-cost measures are implemented, the total reduction could be 34% and the annual savings could be over $80k. Raytheon and other organizations should roll-out this low-cost process across all existing data centers to not only increase their energy efficiency, but also to change the energy consuming behavior of their professional staff.

While these results are impressive, they highlight two problems that many data centers have – poor initial design that does not include an emphasis on energy efficiency and poor day-to-day monitoring of the data center's electricity consumption. In order to remedy these problems, management must utilize incentives and performance management to drive behavior change during the design process. In addition, similar management techniques must be used to engage employees and set continuous improvement goals so that the electricity consumption of data centers decreases over time. During this project, the improvement process was broken down into three phases. This phased approach allowed the team to test a behavior change process on the IT organization responsible for the data center. We first highlighted the overall problem (low energy efficiency). Then, we helped the employees brainstorm improvement ideas, and encouraged them to implement their suggestions in a manner that allowed us to monitor each action's affects. Finally, we reinforced their positive behavior by illustrating the impact to both the employees and to the employees' management team. This simple, well established behavior change model worked to motivate the employees to action.

The next steps for any company that would like to increase the energy efficiency of their data centers is to roll-out the piloted process systematically using rapid results team who are empowered by IT and Facilities leadership to make changes. Lean techniques such as jishuken could be used to ensure feedback is integrated into the piloted process and to maximize the organization's return on data center energy efficiency in both the short and long-term. Because the improvement process outlined in this thesis is low-cost, it provides a foundation for any organization that wants to start improving their data center's energy efficiency. I would encourage organizations that utilize the piloted low-cost process to not simply replicate the process, but rather to work to continuously improve the pilot process to yield more impressive results.

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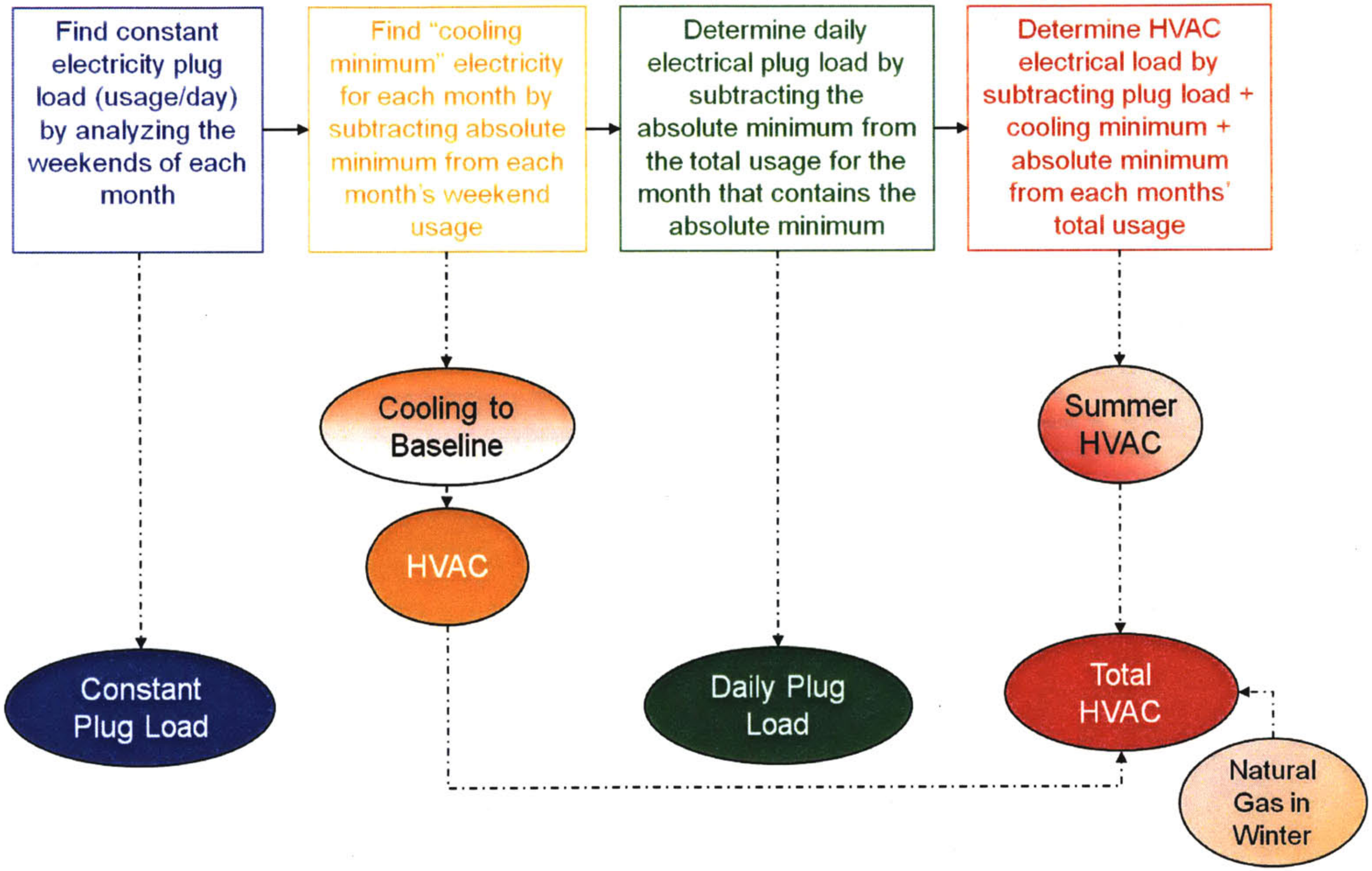
Appendix I – Process for Analyzing Energy Usage



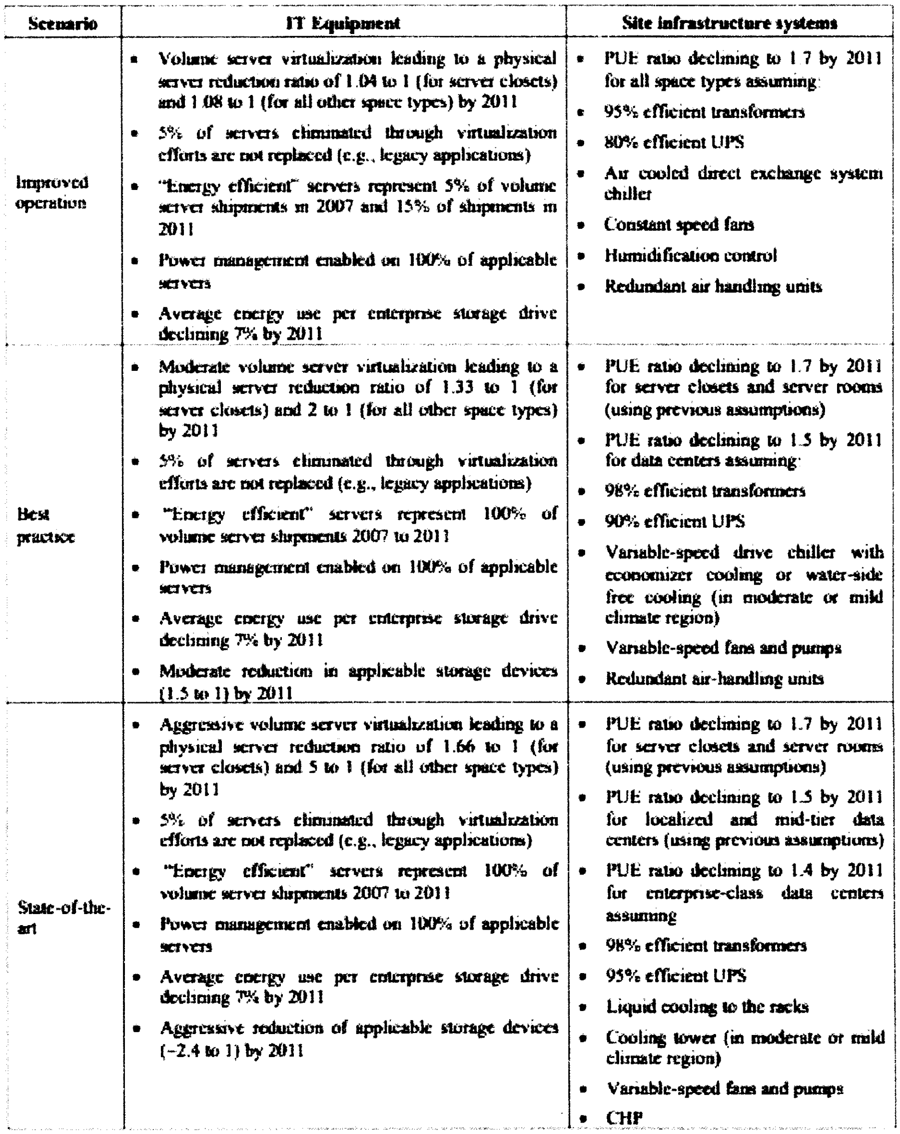
Find constant electricity plug load (usage/day) by analyzing the weekends of each month

Find "cooling minimum" electricity for each month by subtracting absolute minimum from each month's weekend usage

Determine daily electrical plug load by subtracting the absolute minimum from the total usage for the month that contains the absolute minimum

Determine HVAC electrical load by subtracting plug load + cooling minimum + absolute minimum from each months' total usage

Appendix II – Summary of Alternative Efficiency Scenario Assumptions[130]



Scenario	IT Equipment	Site infrastructure systems
Improved operation	• Volume server virtualization leading to a physical server reduction ratio of 1.04 to 1 (for server closets) and 1.08 to 1 (for all other space types) by 2011 • 5% of servers eliminated through virtualization efforts are not replaced (e.g., legacy applications) • "Energy efficient" servers represent 5% of volume server shipments in 2007 and 15% of shipments in 2011 • Power management enabled on 100% of applicable servers • Average energy use per enterprise storage drive declining 7% by 2011	• PUE ratio declining to 1.7 by 2011 for all space types assuming: • 95% efficient transformers • 80% efficient UPS • Air cooled direct exchange system chiller • Constant speed fans • Humidification control • Redundant air handling units
Best practice	• Moderate volume server virtualization leading to a physical server reduction ratio of 1.33 to 1 (for server closets) and 2 to 1 (for all other space types) by 2011 • 5% of servers eliminated through virtualization efforts are not replaced (e.g., legacy applications) • "Energy efficient" servers represent 100% of volume server shipments 2007 to 2011 • Power management enabled on 100% of applicable servers • Average energy use per enterprise storage drive declining 7% by 2011 • Moderate reduction in applicable storage devices (1.5 to 1) by 2011	• PUE ratio declining to 1.7 by 2011 for server closets and server rooms (using previous assumptions) • PUE ratio declining to 1.5 by 2011 for data centers assuming: • 98% efficient transformers • 90% efficient UPS • Variable-speed drive chiller with economizer cooling or water-side free cooling (in moderate or mild climate region) • Variable-speed fans and pumps • Redundant air-handling units
State-of-the-art	• Aggressive volume server virtualization leading to a physical server reduction ratio of 1.66 to 1 (for server closets) and 5 to 1 (for all other space types) by 2011 • 5% of servers eliminated through virtualization efforts are not replaced (e.g., legacy applications) • "Energy efficient" servers represent 100% of volume server shipments 2007 to 2011 • Power management enabled on 100% of applicable servers • Average energy use per enterprise storage drive declining 7% by 2011 • Aggressive reduction of applicable storage devices (~2.4 to 1) by 2011	• PUE ratio declining to 1.7 by 2011 for server closets and server rooms (using previous assumptions) • PUE ratio declining to 1.5 by 2011 for localized and mid-tier data centers (using previous assumptions) • PUE ratio declining to 1.4 by 2011 for enterprise-class data centers assuming • 98% efficient transformers • 95% efficient UPS • Liquid cooling to the racks • Cooling tower (in moderate or mild climate region) • Variable-speed fans and pumps • CHP

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[130] (US Environmental Protection Agency 2007)

Appendix III – List of Electrical Power Calculation Tools[131]

Company	Link	Comments
HP	**TOOL:** http://h30099.www3.hp.com/configurator/powercalcs.asp **WHITE PAPER:** http://search.hp.com/redirect.html?type=REG&qt=power+calculator&url=http%3A//h20000.www2.hp.com/bc/docs/support/SupportManual/c00881066/c00881066.pdf%3Fjumpid%3Dreg_R1002_USEN&pos=1	HP also has a white paper on the tool (see second link)
Dell	**PLANNING FOR ENERGY REQUIREMENTS:** http://www.dell.com/calc	This link includes instructions and Data Center planning tools
IBM	Calculator for the blades and modular product lines (x86 architecture server systems and rack storage), the tool can be downloaded at: http://www-03.ibm.com/systems/bladecenter/resources/powerconfig/ For the Power Processor-based server systems, an online tool is available at the following link: www.ibm.com/systems/support/tools/estimator/energy	
Sun Power Calculators	Tool: http://www.sun.com/solutions/eco_innovation/powercalculators.jsp	
Cisco Power Calculator	Tool: https://tools.cisco.com/cpc/authc/forms/CDClogin.fcc?TYPE=33619969&REALMOID=06-00071a10-6218-13a3-a831-83846dc90000&GUID=&SMAUTHREASON=0&METHOD=GET&SMAGENTNAME=SMGDuJAbSsi7kExzQDRfPKUltt%2bPcjKOjTGlbtk%2fRp7BdNYLiP9lyOBjXBU5PAxlXD&TARGET=http%3A%2F%2Ftools.cisco.com%2Fcpc%2F	Registration required

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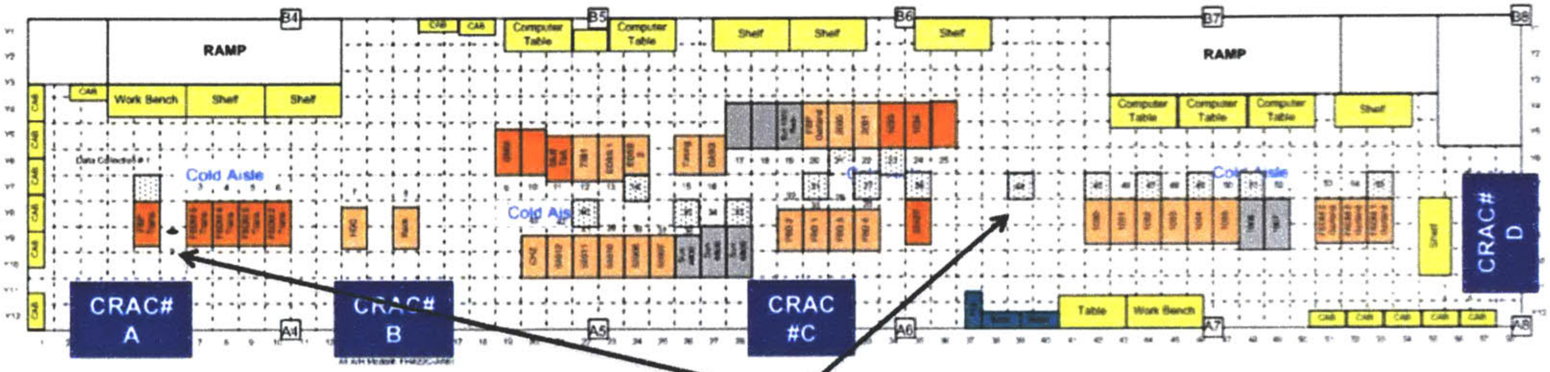
[131] (The Green Grid 2009)

Appendix IV – Changes made to the pilot data center

Prior to Phase I Improvements



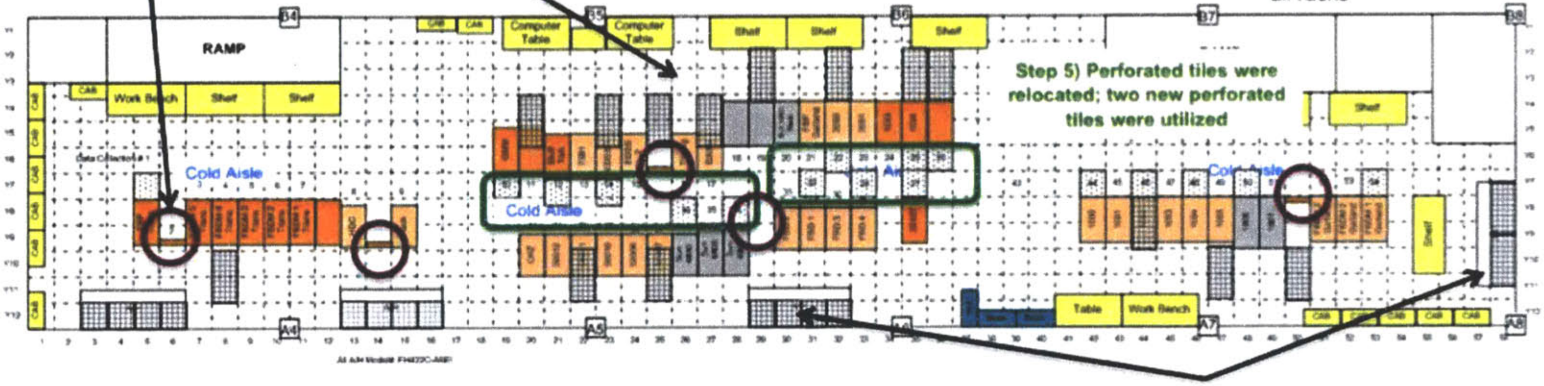
Step 6) Masonite was used as a "blanking rack"

Step 4) 14 - 4' x 2' egg crate ceiling tiles placed in hot aisles

Step 1) Random perforated tiles were replaced with normal floor tiles

Step 2) Foam/rubber was used to stop all cable cut-outs (not shown in drawing)

Step 3) Blanking panels were installed in all racks



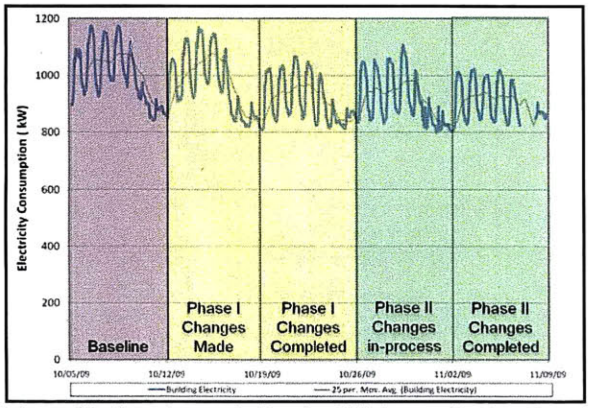
Step 5) Perforated tiles were relocated; two new perforated tiles were utilized

Step 7 (not shown) Chimneys were built on the CRAC units

Step 5) 6 - 2' x 2' and 2 - 4' x 2' egg crate ceiling tiles placed above CRACs

Appendix V – Sensitivity of Chiller's Assumed Electricity Consumption

To understand the sensitivity of the assumed chiller electricity consumption per ton of chilled water, a sensitivity analysis was performed. As seen in Figure 89 and Table 17, the building's electricity consumption decreased by 133 kWh from the week prior to the start of the improvement process to the time in which all improvements had been made. However, when only the constant load, which includes data centers, is analyzed, a drop from about 925 kWh to 825 kWh is observed. Therefore, a value of 100 kWh can be assumed to be the amount of electricity avoided in the data center due to the improvement process.



It is notable that when excluding the chiller's contribution, the pilot data center accounted for 222 kWh in the "Baseline" time period (about 24% of the total constant load) and 170 kWh in the "Phase II Changes Completed" time period (about 21% of the total constant load).

Figure 89: Building Electricity before and after Phase I changes were implemented

Table 17: Analysis of electricity saved during the piloted improvement process

	Baseline	**Phase II Changes Completed**
Total Electricity Consumed (kWh)	167,977	145,654[1]
Average Outside Air Temp (F)	62.7	63.6
Total Reduction of Electricity (kWh)	n/a	22,323
Daily Reduction in Electricity (kWh)	n/a	3,189
Reduction in Electricity (kWh)	n/a	133

[1] Missing data on electricity consumption for Saturday was assumed to be the same as Sunday

Of the 100 kWh avoided, 52.2 kWh can be attributed to the CRAC and the lighting improvements, which leaves 47.8 kWh of avoided electricity that is not accounted for. As mentioned previously, the data center owner copied the improvement process in other data centers during the completion of the pilot, which would have led to some of the decrease. Also, it is reasonable to assume the "typical value of 0.53 kW/ton" is too low for the Garland, TX site. As shown in Table 18, when the assumed 0.53 kWh/ton is used, the savings is only 7.7 kWh. To explore what chiller electricity rate is required to account for the 47.8 kWh of avoided electricity, Excel Solver was used to determine what value would be required to achieve 47.8 kWh. A value of 3.30 kWh/ton was calculated, which is unreasonably large.The correct value is probably between 0.60-0.85 kWh/ton. While 0.53 kW/ton is too low, it was nonetheless used in the analysis in order to be conservative with the savings calculations.

Table 18: Calculations to determine sensitivity of Chiller Electricity Consumption

	Excluding Chiller Electricity		
	Baseline excluding Chiller	**Post Pilot excluding Chiller**	**Change**
Electrical Load (kW)	221.9	169.5	
Daily Electricity Usage (kW/day)	5325.6	4068	-23.6%
	Baseline (kWh)	**Post Pilot (kWh)**	**Change**
Chilled Water Required (Tons)	65.45	50.95	-22.2%
Assumed Chiller kWh/ton	**Baseline (kWh)**	**Post Pilot (kWh)**	**Difference (kWh)**
0.32	20.9	16.3	4.6
0.39	25.5	19.9	5.7
0.46	30.1	23.4	6.7
0.53	34.7	27.0	7.7
0.60	39.3	30.6	8.7
0.70	45.8	35.7	10.2
0.85	55.6	43.3	12.3
1.00	65.5	51.0	14.5
2.00	130.9	101.9	29.0
3.00	196.4	152.9	43.5
3.30	215.8	168.0	47.8
Cost of Electricity/kW	$0.102		
Assumed Chiller kWh/ton	**Change Including Chiller**	**Annual Savings**	
Assumed Chiller kW/ton	**Change Including Chiller**	**Annual Savings**	
0.32	-23.5%	$50,966	
0.39	-23.5%	$51,873	
0.46	-23.4%	$52,780	
0.53	-23.4%	$53,687	
0.60	-23.4%	$54,594	
0.70	-23.4%	$55,890	
0.85	-23.3%	$57,833	
1.00	-23.3%	$59,776	
2.00	-23.1%	$72,733	

Appendix VI – Breakdown of electricity consumption for building containing the pilot data center

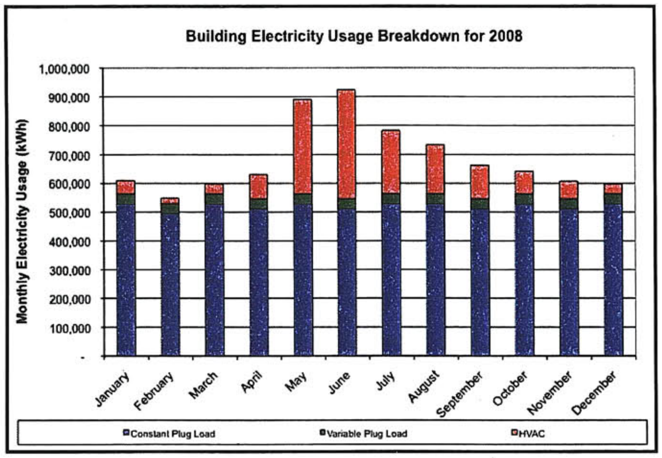


Figure 90: Building's electricity consumption by monthly end use for 2008

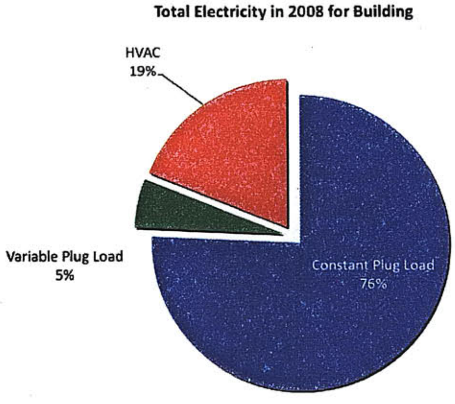


Figure 91: Building's electricity consumption by end use for 2008

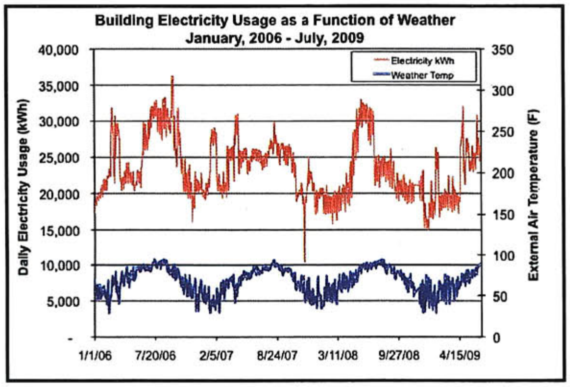


Figure 92: Building's electricity consumption as a function of weather from 2006-2009

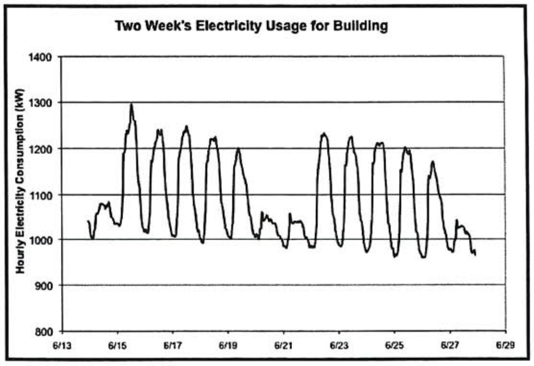
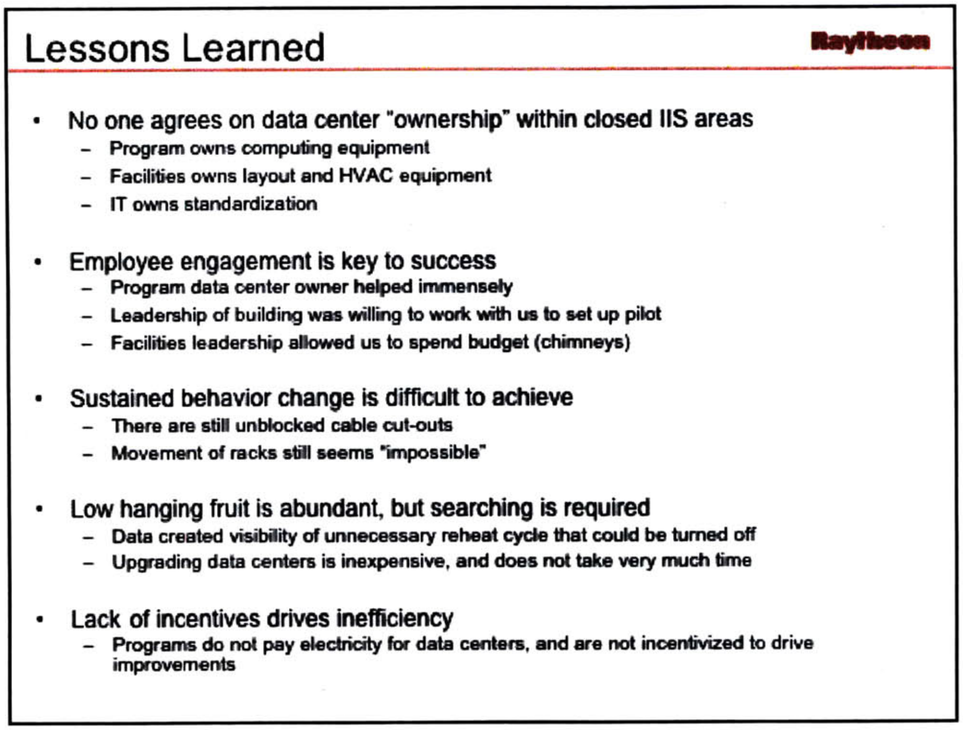


Figure 93: Building's electricity for two weeks in 2009

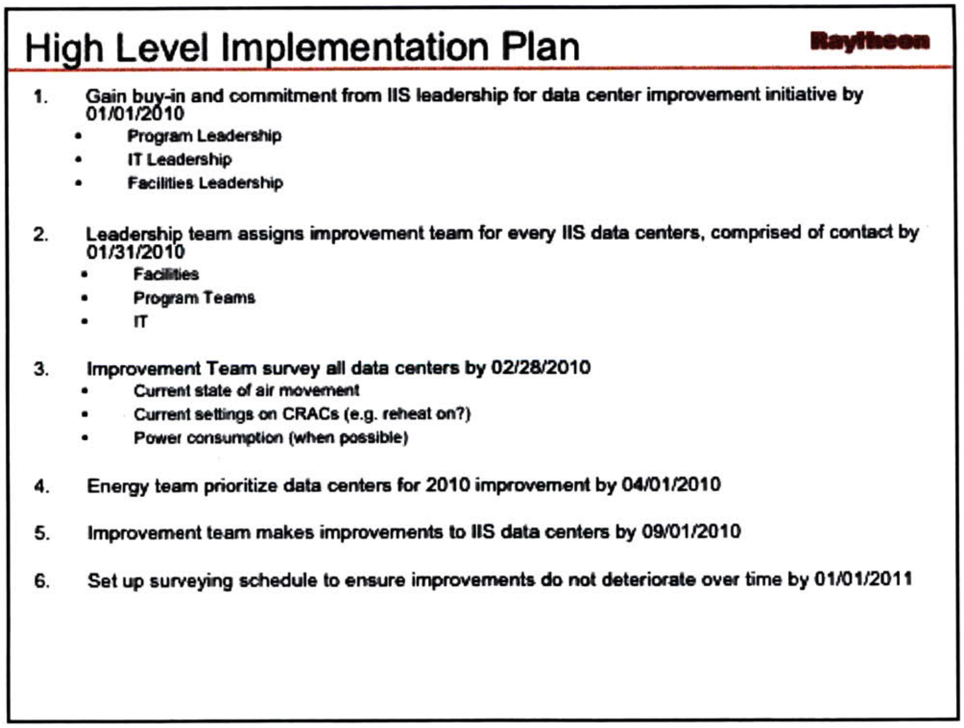
Appendix VII – Specific lessons learned and implementation plan for Raytheon



Lessons Learned

Raytheon

- No one agrees on data center "ownership" within closed IIS areas
  - Program owns computing equipment
  - Facilities owns layout and HVAC equipment
  - IT owns standardization
- Employee engagement is key to success
  - Program data center owner helped immensely
  - Leadership of building was willing to work with us to set up pilot
  - Facilities leadership allowed us to spend budget (chimneys)
- Sustained behavior change is difficult to achieve
  - There are still unblocked cable cut-outs
  - Movement of racks still seems "impossible"
- Low hanging fruit is abundant, but searching is required
  - Data created visibility of unnecessary reheat cycle that could be turned off
  - Upgrading data centers is inexpensive, and does not take very much time
- Lack of incentives drives inefficiency
  - Programs do not pay electricity for data centers, and are not incentivized to drive improvements



High Level Implementation Plan

Raytheon

1. Gain buy-in and commitment from IIS leadership for data center improvement initiative by 01/01/2010
   - Program Leadership
   - IT Leadership
   - Facilities Leadership
2. Leadership team assigns improvement team for every IIS data centers, comprised of contact by 01/31/2010
   - Facilities
   - Program Teams
   - IT
3. Improvement Team survey all data centers by 02/28/2010
   - Current state of air movement
   - Current settings on CRACs (e.g. reheat on?)
   - Power consumption (when possible)
4. Energy team prioritize data centers for 2010 improvement by 04/01/2010
5. Improvement team makes improvements to IIS data centers by 09/01/2010
6. Set up surveying schedule to ensure improvements do not deteriorate over time by 01/01/2011