Energy Research and Development Division
FINAL PROJECT REPORT

VARIABLE AIRFLOW MANAGEMENT

With Direct Expansion Computer Room Air Conditioning (DX-CRAC) Units in Data Centers

Prepared for: California Energy Commission
Prepared by: EPRI

ELECTRIC POWER RESEARCH INSTITUTE

DECEMBER 2013
CEC-500-2015-041

Prepared by:

Primary Author(s):
Dennis Symanski
Brian Fortenbery

EPRI
3420 Hillview Avenue
Palo Alto, CA 94304
www.epri.com

Contract Number: PIR-10-013

Prepared for:

California Energy Commission

Anish Gautam, P.E.
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

ACKNOWLEDGEMENTS

The authors sincerely acknowledge participation and support of the following entities and individuals:

Vigilent Corporation, El Cerrito, CA, for providing wireless sensors and controls system for the direct expansion computer room air conditioning systems as well as monitoring of the equipment performance. Several individuals, including Cliff Federspiel and Sameer Desai, provided technical and operational support.

The EPRI Information Technology Group in offering one of its data center sites in Palo Alto for demonstrating the airflow-management solution with variable-speed drive on its air-cooled DX CRAC units, and the EPRI Facilities Team in supporting the field demonstration.

NetApp in Sunnyvale, CA, for offering one of its small data centers for demonstration of the airflow-management solution with variable-speed drives on its DX CRAC units and supporting field demonstrations. Special thanks to Ralph Renee, David Shroyer, and Alex Mandrusov from NetApp who provided support and coordination.

Liebert Power & Cooling Emerson Network Power, for its support and providing performance data for its air-cooled DX CRAC units at different airflow rates at one of the field demonstration sites.

Compu-Aire, Inc., Whittier, CA, for its support and providing performance data on its water-cooled DX CRAC units at different airflow rates at one of the field demonstration sites.

M. Khattar for guidance, technical support, and assistance with the project.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Variable Airflow Management with Direct Expansion Computer Room Air Conditioning (CRAC) Units in Data Centers is the final report for the "Demonstration of the Effectiveness of Airflow Management with Retrofit of Variable Speed Drives on Existing DX-CRAC Units" project (grant number PIR - 10 - 013) conducted by EPRI. The information from this project contributes to Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

When the source of a table, figure or photo is not otherwise credited, it is the work of the author of the report.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

This report discusses the retrofit of variable-speed drives for air handler fans in direct expansion computer room air conditioning systems which are common in small to mid-sized data centers. It discusses what level of energy savings can be achieved with this approach and how to identify opportunities for energy savings from retrofitting these systems in existing data centers. It is common to supply two to three times the minimum airflow required in order to overcome losses from duct air leakage and air flow short circuiting, and to prevent recirculation of hot air to the information and communications technology equipment. Reducing airflow is one of the most cost-effective means of reducing power demand and energy use in data centers, and is not disruptive to the information and communications technology load. It reduces not only direct energy use by the fans but also indirect cooling energy use from reduced fan heat losses. In existing data centers, it can make cooling capacity available for addition of more information and communications technology equipment in the data center, cooling which would otherwise be used to overcome extra heat generated by fans and inefficient airflow.

This report documents how variable speed drives, also known as variable-frequency drives, were used successfully with both air-cooled and water-cooled type direct expansion computer room air conditioning units to save energy in two small data centers. It was demonstrated that the speed of indoor air fans in direct expansion computer room air conditioning units could be safely reduced to 60 percent of the rated airflow. In this case cooling energy use per unit of the information and communication technology equipment energy use was reduced by 32 percent.

Keywords: Data Center, Computer Room Air Conditioner, CRAC, Direct Expansion, DX CRAC, Variable-Speed Drive, VSD, Variable-Frequency Drive, VFD, Energy Efficiency

Please use the following citation for this report:

Symanski, Dennis; Brian, Fortenbery. (EPRI). 2012. ***Variable Airflow Management with Direct Expansion (DX) Computer Room Air Conditioning (CRAC) Units in Data Centers.*** California Energy Commission. Publication number: CEC-500-2015-041.

TABLE OF CONTENTS

Acknowledgements ..... **i**

PREFACE ..... **ii**

ABSTRACT ..... **iii**

TABLE OF CONTENTS ..... **iv**

LIST OF FIGURES ..... **v**

LIST OF TABLES ..... **vi**

EXECUTIVE SUMMARY **1**

Introduction 1

Objectives 2

Approach 2

Results 3

Conclusions and Recommendation 4

CHAPTER 1: Introduction **5**

1.1 Energy Use in Data Centers 5

1.2 Energy Use for Airflow in Data Centers 6

1.3 High Fan Energy Use in Data Centers 8

1.3.1 Redundancy 8

1.3.2 Actual Data Center ICT Loads versus Design Loads 9

1.3.3 Air Leakage and Bypass 9

1.3.4 Preventing Hot Spots or Hot Air Recirculation 10

1.3.5 Short Circuiting 10

1.4 Airflow Variation in Data Centers 11

CHAPTER 2: Varying Airflow with DX Air Conditioning Equipment and Use of Variable Speed Drives **14**

2.1 The Market for DX CRAC Units 14

2.2 Airflow in Cooling Equipment 15

2.3 Reducing Excess Airflow 16

2.4 Reducing Airflow in DX CRAC units 17
2.4.1 Potential of Condensate to Freeze on Cooling Coil: Not True 17
2.4.2 Potential Lower Energy Efficiency at Lower Airflow Rates: Not True 17
2.4.3 Potential Mechanical Failure at Low Airflow Rates: Not Likely 18
2.4.4 VSDs on DX CRAC Unit Fans: Yes! 18
2.4.5 Manual or Automatic Control of VSD: Either Way it Saves Energy 18
2.4.6 Containment: Optional 18
CHAPTER 3: Field Demonstrations 21
3.1 Methodology 21
3.2 Demonstration Sites Description 22
3.2.1 EPRI Data Center 22
3.2.2 NetApp Data Center 23
3.2.3 Significance of Refrigerant Circuiting in DX CRAC Units 25
CHAPTER 4: Results and Discussion 26
4.1 EPRI CRAC Unit Performance with Reduced Fan Speeds 28
4.2 Compressor Run Times at Reduced Fan Speeds 33
4.3 Energy Savings with Reduced Fan Speeds 34
CHAPTER 5: Indentifying Opportunities for VSDs in Retrofit Applications and Estimating Energy Savings 37
5.1 Case Study 1 40
5.2 Case Study 2 41
APPENDIX A: Test Data A-1

LIST OF FIGURES

Figure 1: Range of Relative Energy/Power Used by Different Subsystems in Data Centers 7
Figure 2: Air Leakage and Bypass around ICT Racks in Data Centers 9
Figure 3: Hot Air Recirculation around ICT Racks in Data Centers 10
Figure 4: Effects of Air Short Circuiting in Data Centers 11
Figure 5: Schematic and Picture of Individual Rack Containment 19

Figure 6: Importance of VSD on Cooling Equipment with Containment.....20
Figure 7: Thermal Map Showing Temperature Distribution in EPRI Data Center 23
Figure 8: Thermal Map Showing Temperature Distribution in NetApp Data Center.....24
Figure 9: Cooling Seasonal Energy Efficiency Ratio of a DX CRAC Unit versus Airflow 27
Figure 10: Cooling Seasonal Energy Efficiency Ratio of a DX CRAC Unit versus Airflow 27
Figure 11: Supply Air Temperatures at Different Airflow Rates in a DX CRAC Unit.....28
Figure 12: Snapshot of the EPRI DX CRAC Unit's Performance.....29
Figure 13: CRAC Units Supply & Return Air Temperatures (EPRI) 31
Figure 14: CRAC Units Supply & Return Air Temperatures 9EPRI) 31
Figure 15: CRAC units Supply & Return Air Temperatures (EPRI).....32
Figure 16: CRAC Units Supply & Return Air Temperatures (EPRI) 32
Figure 17: Measured Fan Power at Different Fan Speeds at EPRI Installation 33
Figure 18: Compressor Run Time Fraction versus Fan Speed.....34
Figure 19: Energy Use by ICT and DX CRAC Cooling Equipment at Different Fan Speeds.....35
Figure 20: DX CRAC Unit Total Energy Use versus Fan Speed for Each Unit of ICT Power.....35
Figure 21: Cooling PUE with DX CRAC Units at Different Fan Speed Settings.....36
Figure 22: Total Cooling (Fans and Compressors) Energy Savings at Different Fan Speeds.....36
Figure 23: Direct Plenum Return to Reduce Hot Spots and Short Cycling 37

LIST OF TABLES

Table 1: Seasonal Energy Efficiency Ratio under various conditions.....26

EXECUTIVE SUMMARY

Introduction

It is common practice in data center cooling to supply two to three times the amount of cold airflow actually needed in order to overcome losses from duct air leakage and air flow short circuiting, and to prevent recirculation of hot air back to the information and communication technology equipment. Reducing excessive airflow is one of the most cost-effective means of reducing power demand and energy use in data centers. It is non-disruptive to the information and communications technology load and also reduces both direct fan energy and cooling energy required to compensate for fan heat. In existing data centers, reducing excessive airflow can make available cooling capacity that is otherwise needed to overcome extra heat generated from fans and inefficient airflow. This can enable the addition of more information and communications technology equipment in the data center to increase computing density.

It is now well accepted that variable airflow distribution in data centers is essential for energy efficiency. While variable speed drives have been successfully used on chilled water computer room air conditioning unit fans, their use on direct-expansion computer room air conditioning unit fans is rare. Manufacturers have developed new direct expansion computer room air conditioning units with variable airflow along with modulating compressor capacities that provide correspondingly less cooling at lower fan speeds. However, use of variable speed drives on existing direct expansion computer room air conditioning units where compressors do not have capacity modulation capabilities presents unique challenges that have discouraged the use of this technology. Successful demonstrations of variable speed drives on existing direct expansion computer room air conditioning units would help small and medium-sized data centers save energy. Today, the vast majority of data centers in California and elsewhere use direct expansion-based computer room air conditioning units due to the many benefits they offer. It is estimated that there are over 2.5 million of these data centers in the United States. Very few of these have modulation capability. This presents a large opportunity for them to be retrofitted and become more efficient. This demonstration project extended the use of variable speed drives to direct expansion computer room air conditioning units and demonstrated its benefits.

Resistance to the use of variable speed fans in data centers has mainly been driven by the perceived fear that variable speed operation of data center cooling may adversely affect reliability. The use of variable speed drives on direct-expansion units does pose some additional challenges. In particular, when airflow rate is reduced, the cooling coil temperature in a direct-expansion unit is also reduced, and reduced coil temperature would condense more moisture, and in extreme cases would freeze the condensate on the coil. But this argument is more rhetorical than real. If minimum airflow is controlled by using reheat in such a manner that the supply air temperature does not fall below, say 45 F, it is unlikely to cause any condensate freeze up issue.

Proper airflow management also requires effective separation of the hot and cold airflows within a data center to prevent recirculation of hot air back to the information and communications technology equipment. The physical barrier for separation of the hot and cold

air is expensive and often impractical. A conventional hard-wired distributed network of temperature sensors at the inlet of the information and communications technology equipment is used to identify where hot spots are, and the information is used to provide selective and localized barriers to prevent mixing and control the speed of fans for management of airflow. A wireless sensor network such as that manufactured by Vigilent is a more cost effective and practical solution as compared to the alternative of physical barriers between hot and cold air to prevent hot air recirculation.

Objectives

The primary objectives of this project were to: 1) demonstrate reliable operation of indoor air distribution fans which were retrofit with variable speed drives in compressor-based direct-expansion computer room air conditioning units, 2) document energy savings from such use of variable speed drives in small to medium data centers that use direct expansion computer room air conditioning units; and 3) demonstrate use of distributed wireless network of temperature sensors to monitor and control the variable speed drives in direct expansion computer room air conditioning units for airflow management.

Approach

Two small data centers were selected for demonstration of this technology. Each data center has two direct expansion computer room air conditioning units. Each unit is sized to meet the entire data center load with both units being operated at the same time at approximately one-half load. If one unit fails or requires servicing, the remaining unit is operated at full load thus providing redundancy. One of the data centers has air-cooled condensing units with direct expansion computer room air conditioning units while the other data center has water-cooled condensing units with direct expansion computer room air conditioning units. The air cooled units have two compressors each with their own independent refrigerant delivery circuit but intertwined cooling coils. The water cooled units also have two compressors with independent refrigerant circuits, but with independent cooling coil sections instead of a single intertwined cooling coil. The air-cooled system distributes cold air to the server room through perforated floors, and the return air is drawn directly from the server room space to the top of the computer room air conditioning unit. It has no features for containment of hot or cold air. The water-cooled computer room air conditioning units deliver cooled air through conventional overhead ducts, and the return air is brought back to the air conditioning units through a ceiling plenum. Heated air exhausted by the servers and cold air delivered by the air conditioners is kept separated by containing cold air in the aisles with vinyl curtains above the racks to the ceiling. The air cooled and water cooled units at the two data centers were supplied by two different manufacturers and the units in both facilities are over 10 years old. The two demonstration sites provided a good spectrum and wide range of possible field applications.

The indoor air distribution fan motors on the direct expansion computer room air conditioning units were retrofitted with variable speed drives. The motors were not replaced even though these were not rated for inverter duty. Since the motors are in the cold air stream, they were considered not likely to heat up and fail due to possible heat build up from the variable speed drives. The researchers were aware of similar non-inverter duty motors in chilled water

computer room air conditioning units with variable speed drives that have been operating for the last 4 years without any issues. These computer room air conditioning units fan motors have now been operating for more than a year without any apparent problems.

The variable speed drives were initially controlled manually, and fan speeds were gradually reduced from 100% to 60% in 10% steps. At each step, the units were allowed to operate for many days, and supply air temperatures were monitored closely to observe whether any issues would occur. Only after the operating staff was comfortable that the step reduction was effective, was the fan speed changed again. After the initial tests under manual mode of operation for fan speed control, Vigilent wireless controls were used to automatically step down the fan speed. The Vigilent system consists of a set of distributed wireless temperature sensors at the air inlet of the information and communication technology equipment to gathered temperature profiles and use the data to vary speed of computer room air conditioning unit fans to avoid hot spots.

Results

The results were very encouraging, and energy savings were very substantial. Even at the lowest fan speed of 60%, the supply air temperature rarely dropped below 45^0 F, and no visible signs of condensate freeze up were observed on the cooling even though the system operated at the lowest fan speed setting for extended periods of time through winter and summer conditions typical of California.

At 60% fan speed, over 88% of the fan energy was saved. In addition, the heat losses from the fan motor also decreased, providing further energy savings for compressors. At 60% fan speed, total cooling energy was reduced by 32% as compared to the cooling energy required at 100% fan speed. The total energy savings achieved was 19.4% of the total energy used by all of the Information and Communications Technology (ICT) equipment in the facilities, for the EPRI datacenter this resulted in savings of approximately 140,000 kWh/annually. The annual electricity cost savings for the EPRI datacenter was approximately $12,000, at $0.08/kWh, for a 1.5 year payback period for the retro-fit project (without any utility incentives).

The total cooling energy savings at other fan speeds were also significant: 18.1%, 19.7%, 26.5%, and 32%, respectively at 90%, 80%, 70%, and 60% fan speeds as compared to cooling energy use at 100% fan speed. The partial cooling-only power usage effectiveness index also reduced by 8.7%, 12.2%, 16.7%, and 19.4% at 90%, 80%, 70%, and 60% fan speeds, respectively. The power usage effectiveness metric, championed by The Green Grid, represents a ratio of the total energy use in a data center that includes the information and communications technology equipment as well as all supporting infrastructure equipment, to the energy use by the information and communications technology equipment alone. A partial cooling-only power usage effectiveness rating here refers to the ratio of the energy use by the information and communications technology equipment and the cooling-only infrastructure equipment divided by the information and communications technology equipment energy use.

Conclusions and Recommendation

Variable speed drives on direct expansion computer room air conditioning units can be utilized effectively to provide energy savings. Variable airflow is now widely accepted in data centers with chilled water cooling systems. This project demonstrated that variable speed drives can also be successfully used with both air- and water-cooled non-modulating direct expansion computer room air conditioning units. When using variable speed drives with direct expansion computer room air conditioning units, minimum fan speed setting above 67% is generally recommended by manufacturers, though minimum speed settings at 60% did not cause any issues with two different types of direct expansion computer room air conditioning units, air cooled and water cooled, from two different manufacturers in the 18-month demonstration. The additional energy savings from lower speed setting at 60% versus 67% are quite small (~88% versus ~80%). Additional compressor energy savings, about a half to a third of the fan energy savings, are also derived from reduction of heat generated by the fan motor when the fan speed is reduced from 100% to 60%.

It is preferred that variable speed drives be installed only on inverter rated fan motors, but there does not appear to be any justification for not installing them on non inverter-rated motors typical of older equipment. Some field experience has shown that non-inverter rated motors can last a long time, at least several years, after installation of variable speed drives.

Containment of hot or cold air is preferred in data centers to avoid hot spots, but it is not necessary to have containment to benefit from the use of variable speed drives.

A fully automatic variable speed drive control system with distributed temperature sensors is preferred because it automatically responds to changes in the data center and reduces risks. However, in small data centers where automatic control systems may be too costly, manual control of variable speed drive can still provide significant energy savings. A manual control may not yield the maximum possible savings because it may not be easy to set the fan speed at minimum possible levels. It would still provide meaningful savings according to physical laws for fans that indicate that the initial 10% reduction in fan speed provides more energy savings (~27%) than the subsequent incremental 10% reduction in fan speeds (~22%, 17%, and 13%, respectively).

CHAPTER 1: Introduction

The primary objectives of this project were to demonstrate that: 1) conventional Direct eXpansion (DX) Computer Room Air Conditioning (CRAC) unit air distribution fans could be safely retrofitted with Variable Speed Drives (VSD) and 2) such retrofits could yield significant energy savings. Secondary objectives were to better manage air distribution in data centers to reduce hot spots using distributed temperature sensors in data centers and reduce airflow requirements.

It is now well accepted that variable airflow distribution in data centers is essential for energy efficiency. While VSDs have been successfully used on chilled water CRAC unit air distribution fans, lately in the data center industry, their use on DX CRAC units' fans are rare. Manufacturers have developed new DX CRAC units with variable airflow by modulating fan speeds. Such units are also equipped with modulating compressor capacities such that they provide correspondingly less capacity at lower fan airflows. However, use of VSDs on existing DX CRAC units where compressors do not have capacity modulation capabilities presents unique challenges that have kept back many users from using this technology. Successful demonstrations of existing DX CRAC units with VSDs would help a very large number of small and medium-sized data centers.

1.1 Energy Use in Data Centers

Energy to power data centers that house Information and Communication Technology (ICT) equipment is growing rapidly. Energy is required not only for powering the ICT equipment but also for cooling equipment that removes heat generated from the ICT equipment as well as power conditioning equipment to provide an uninterrupted supply of power to the ICT equipment.

Although data centers are often associated with buildings that house large numbers of the ICT equipment, not all data centers are large. These can be as small as a single rack of ICT equipment that is placed in a closet in an office, for example, to manage its telephones and emails, to rooms containing a few racks to small data centers that may often be called computer rooms, server rooms, ICT rooms or labs, but they essentially act as data centers because the heat generated by the ICT equipment must be removed by cooling equipment. There are some 2.5 million such data centers in the U.S., with most of them contained within commercial office buildings.

In the last few years, leading users of ICT equipment have developed some very efficient data centers that have greatly reduced the need for power to cool, especially in large enterprise data centers within buildings dedicated for that purpose. Power usage effectiveness (PUE), a metric championed by the Green Grid and defined as a ratio of the total facility energy use divided by the energy use by the ICT equipment, is generally used to define the efficiency of its cooling and power distribution infrastructure. The Uptime Institute reports an average PUE of 1.8 from its 2011 survey of more than 500 data centers. In another study of more than 100 data centers for its

ENERGY STAR program in 2009, the Environmental Protection Agency (EPA) reported an average PUE of 1.91. A PUE of 1.91 indicates that 0.91 kilowatt-hours (kWh) is required to support each kWh used by the ICT equipment. The support power is primarily for cooling infrastructure, but it also includes power losses in electric power distribution infrastructure to provide uninterrupted power to the ICT equipment and other miscellaneous uses of electricity in a facility such as lighting. Data centers are typically designed to provide continuous and uninterrupted operation of the ICT equipment that require special equipment to condition and distribute power. Its infrastructure is designed with sufficient redundancy and backup.

The state of the art in cooling large enterprise scale data centers that use about 10 megawatts MW or more power has rapidly evolved in the last few years. Coupled with the use of air side economizers as well as advances in the ICT equipment that can operate under a wider range of inlet air temperature and humidity, some enterprise scale data centers have reported PUEs as low as 1.1 or lower.

However, most data centers, large and small, use traditional air conditioning systems that remove heat from the data center space and reject it to the ambient air. The heat is removed from the ICT equipment by cold air, which is provided by traditional air conditioning equipment. Large data centers generally use chilled water based cooling systems, while smaller and mid size data centers often use DX CRAC units.

1.2 Energy Use for Airflow in Data Centers

A study of thirteen data centers by Uptime Institute found that the data centers had an average of 2.6 times more cooling capacity than they needed (Uptime Institute White Paper TUI3010)[1]. The excess cooling capacity is coupled with excess airflow. The excess airflow bypasses the ICT equipment and often causes hot spots. The study also found that when bypass airflow was reduced, the cabinet inlet air temperatures also dropped and hot spots were eliminated or reduced.

When cooling capacities greatly exceed ICT loads and airflow within the data center space is poorly managed, it will lead to energy waste and hot spots within the space. Consider data centers with DX cooling systems: If cooling capacity is more than what is needed by the ICT equipment, its compressors will shut off, but its fans will continue to move air through it. The supply air becomes a few degrees warmer than the return air as it picks up heat dissipated by the fan motor. Therefore, hot air is delivered to the cold aisle from those DX units whose compressors are turned off due to overcapacity. It is obvious that this hot air will cause hot spots at the inlet of the ICT equipment.

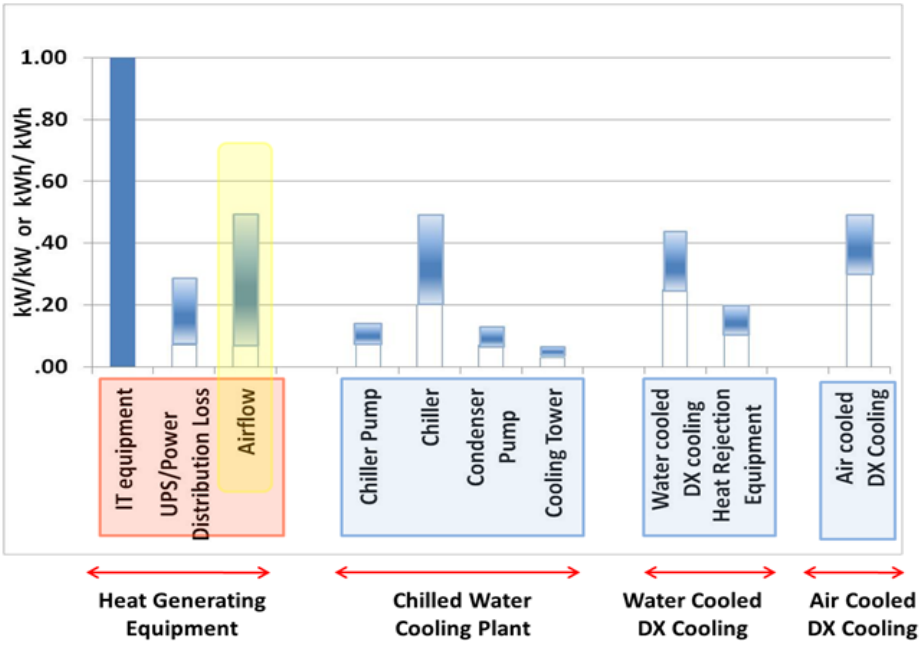
A breakdown of energy consumption by different components of the support infrastructure from a Lawrence Berkeley National Laboratory (LBNL) study of 25 data center sites is plotted in Figure 1.[2] Energy use by three major components and subsystems—uninterruptible power

[1] http://www.schneider.co.il/site/upload/uploaded/Bypass_Airflow_White_Paper--Full.pdf

[2] http://hightech.lbl.gov/benchmarking-dc.html

supply (UPS), air-distribution equipment, and cooling subsystem—for each kWh unit of the ICT equipment energy use is plotted in the figure. The low, high, and typical values are shown with graded color bars. These data are quite similar to other data reported in the literature and trade press. Some additional data from literature are also used in the plot to show expanded range of energy use for each subsystem.

Figure 1: Range of Relative Energy/Power Used by Different Subsystems in Data Centers



The figure shows energy use by the ICT equipment as unity. All other energy uses are relative to the unity ICT energy use. All energy used by the ICT equipment turns into heat that must be removed by the air-conditioning equipment.

The UPS required for reliability in power distribution accounted for a low of 0.07 to a high of 0.28 kWh/kWh of the IT equipment among different data centers in the study. New UPS configurations such as "eco" mode of operations and some rotary UPS systems can cut down losses further to just about 0.03 kWh/kWh of the ICT equipment. The efficiency of UPS devices varies with the ICT load; lightly loaded UPS systems are less efficient and waste more energy. Not only does the inefficiency of the UPS cause direct loss of power, but its inefficiency also turns into heat in data centers and requires additional energy for cooling.

The air-distribution fans accounted for a low of 0.07 to a high 0.50 kWh/kWh of the ICT equipment. The air-distribution fans are located within the data center space, and any energy use by these fans is eventually converted into heat that must be removed by the air-conditioning equipment. Therefore, the energy use by air-distribution fans is plotted next to the heat-generating equipment such as ICT equipment and UPSs. Since the LBNL study, some data

centers have reported fan power consumptions of as low as 0.02 kWh/kWh of the ICT equipment, especially in closed coupled air distribution systems such as in-row coolers with hot air containment.

The heat generated by the ICT equipment, UPS system, and the air-distribution fans must be removed by the cooling systems. Energy use for three common types of cooling subsystems is included in the figure. Other variations of cooling systems are possible, such as air-cooled chiller versus water-cooled chiller shown in the figure, as well as air-side economizers, which are not discussed in detail here because the focus of this document is airflow management with DX cooling equipment.

The air-moving fans show the widest range of data, from a low of 0.07 to a high of 0.50 kWh/kWh of the ICT power, or a ratio of approximately 7 to 1 between the highest to the lowest number. If you consider lower fan power numbers of 0.02 reported since the study, the range between the higher and lower energy use numbers become even wider.

The wide range of power required for airflow clearly shows that addressing it offers one of the most promising opportunities for energy savings in data centers. The direct fan energy savings in data centers also lead to cooling energy savings from reduced fan heat, which lowers the data center cooling requirement. The combined savings provide additional incentive to address fan energy savings.

1.3 High Fan Energy Use in Data Centers

The primary reason for use of very high fan power in data centers is perhaps because of perceived reliability. Excess capacity may be perceived to provide more reliability; on the contrary, it wastes energy and may lower reliability by causing hot spots within a data center. Several reasons may contribute to excess airflow and high fan energy use, and some are discussed below. Their combined effect is that two to three times more airflow than the minimum required may be taking place. Excess airflow does not do any productive work; it just circulates within the data center, causes hot spots, increases energy use for air movement, and adds excess fan heat to the space. Preventing excess airflow would help reduce hot spots and fan energy use.

1.3.1 Redundancy

Cooling and airflow equipment in configuration of N+1 or N+2 (one or two units more than what is required to meet the total load) is generally specified for redundancy in data centers due to reliability requirements and the continuous nature of operation. The redundant equipment is in place to provide sufficient cooling in the event of an unforeseen loss of a unit either due to failure or planned service outage. Where multiple distributed CRACs or computer room air handlers (CRAH) are used, it is common to specify one redundant CRAC or CRAH for each five to seven units or provide about 15 to 20% extra capacity. These redundant units typically operate in full service during normal operation and share the space heat loads. Therefore, it is quite common to see 15% to 20% more airflow and fan power than the design load and it adds to the fan energy use.

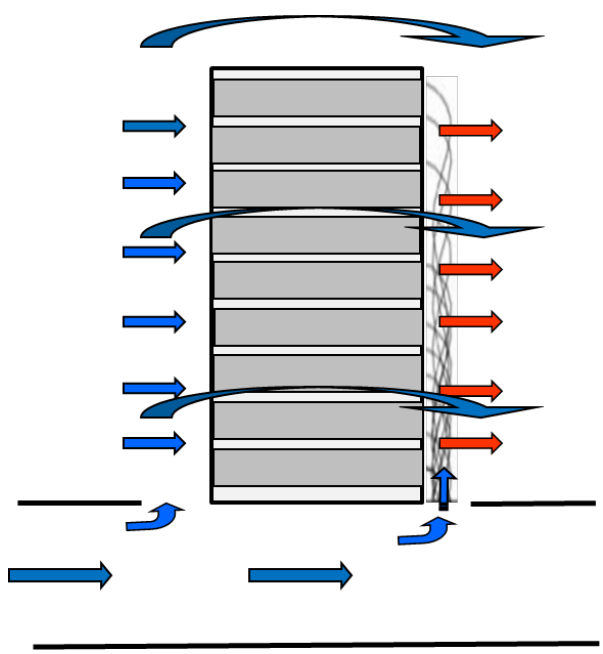
1.3.2 Actual Data Center ICT Loads versus Design Loads

Most data centers operate at lower-than-design ICT loads. This is a quite common practice; data center operators prefer to keep ICT load below 80% of its capacity, while many data centers operate at even lower loads. It is not uncommon to see data centers actually operating below 50% capacity as data centers owners design larger data centers than what is immediately needed to accommodate future growth. Even at 80% loading, heating, ventilating, and air conditioning (HVAC) airflow and fan equipment is 25% oversized, and coupled with redundancy, fan equipment capacity could be 50% more than needed.

1.3.3 Air Leakage and Bypass

In traditional data centers, cold supply air is delivered to heat-generating equipment from under the floor through perforated tiles in front of racks. Power and communications cables are also distributed under the floor through tile cutouts (usually in the back of the racks). The cable cutouts are not sealed, and air easily leaks through them. These cutouts are often in the hot aisle, so the leaked air does not do productive ICT equipment cooling and simply circulates in the data center, causing extra fan energy use. Air may also leak from openings between adjacent ICT equipment within racks, blank spaces left open to accommodate future ICT equipment within racks, spaces between adjoining racks, or spaces left open to accommodate future racks. A schematic of air leakage around an ICT rack is shown in Figure 2. Any air leakage requires additional but unproductive airflow and adds extra fan energy use. Preventing air leakage will reduce airflow needs and fan energy use. There are several products in the market to help prevent air leakage such as blanking panels that are often used to block such air bypass from partially loaded racks.

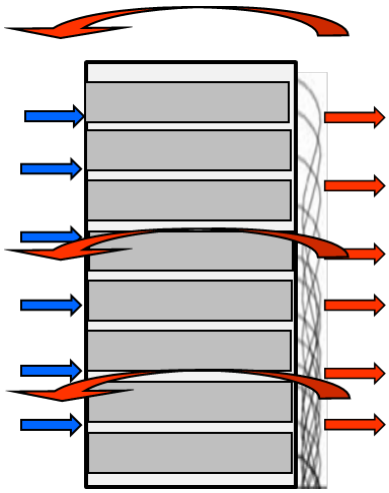
Figure 2: Air Leakage and Bypass around ICT Racks in Data Centers



1.3.4 Preventing Hot Spots or Hot Air Recirculation

It is a common practice to blow extra cold air in order to reduce hot spots and reduce hot air recirculation in a data center. Hot exhaust air from the ICT equipment can re-circulate back to the inlet of the IT equipment, as shown in Figure 3: Hot Air Recirculation around ICT Racks in Data Centers**.** The recirculation generally takes place due to local conditions such as blockage of air discharged from the ICT equipment by cables and wires, which causes the hot air to be drawn back at the inlet of the ICT equipment. The air may also re-circulate at the end of a row of equipment. The recirculation is also observed near the top of the equipment rack, where it is easier for the ICT equipment rack to pull hot discharge air adjacent to the equipment than the cold air coming out of a floor outlet.

Figure 3: Hot Air Recirculation around ICT Racks in Data Centers

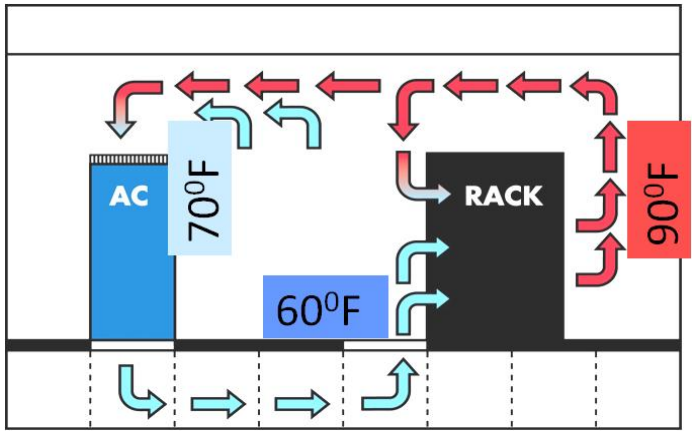


1.3.5 Short Circuiting

In some cases, CRAC or CRAH units are laid out in such a way that some of the cold supply air simply returns back to the CRAC or CRAH without doing any useful cooling as a result of short circuiting of the cold air. This can be reduced by properly locating air distribution tiles and the return air intake. There are some products in the market that would allow hot air to be ducted directly back to the CRAC return air plenum and prevent its mixing with the cold air.

Excess airflow also makes the CRAC unit operate at lower efficiency. Excess cooled air that bypasses the ICT equipment mixes with the hot discharge air from the IT equipment before it returns to the CRAC. The mixed return air temperature is thus lower than ideal when it enters the CRAC unit and lowers the CRAC unit operating efficiency. Figure 4 shows a schematic of air temperatures with bypass quantity that is twice that of the airflow across the ICT equipment.

Figure 4: Effects of Air Short Circuiting in Data Centers



This is one of the reasons why the thermostat set points are kept so low in data centers. In the above figure where three times more airflow is circulated than the minimum required through the ICT equipment, the return air thermostat has to be set to a low temperature of 70°F, even when hot air at the outlet of the ICT equipment is 90°F.

It is clear that airflow in most data centers is much more than the required minimum. One way to reduce the airflow is to use variable speed drives (VSD) on CRAC fans that will allow them to match the airflow from the CRAC units to the airflow required by the ICT equipment.

1.4 Airflow Variation in Data Centers

Until recently, data centers were routinely designed with constant airflow. The often-cited argument is that the cooling loads in data centers remain relatively unchanged, and VSDs are not economically justified. This argument, however, was debunked in 2004 in a large-scale enterprise data center for Oracle located in Austin, Texas. In this installation, VSDs on the chilled-water CRAC units were implemented; the actual payback period was observed to be less than 6 months as compared to an estimated payback period of 19 months. (Ref: Khattar, American Society of Heating, Ventilating, Refrigeration, and Air Conditioning Engineers [ASHRAE] paper). With chilled-water CRAC units, there is no concern of potential condensate freeze up, and the fan speed can be reduced to levels below 60%. However, many CRAC units are traditionally equipped with electric heat elements that require a minimum airflow for safe operation. The minimum airflow is typically about 50%. At 50% fan speed, however, fan energy savings of about 87% are expected based on the cubic fan laws.

It is true that the data center loads remain relatively unchanged from hour to hour but can change over a period when new ICT equipment is installed or old equipment is retired. The data centers are also usually provisioned with extra cooling capacity for future growth. The data center design requires redundancy in cooling so that the failure of a single unit will not bring down the entire data center. Large data centers are designed with typical redundancy of approximately 15%; generally one extra CRAC unit is provisioned for each 5 or 6 units. If

airflow could be reduced just by the redundant capacity of 15%, the fan law would dictate that 38.6% of the direct fan energy would be saved. In addition, a fan running at 85% instead of 100% would dissipate less heat to the air flow, which would reduce energy required to cool the air and provide further energy savings.

In real-world scenarios, the airflow can be reduced more than by just the redundant capacity, at least for some time during which the data center is being gradually populated with the ICT equipment. During this period, a fan would actually run at much lower than 85% speed, providing even more savings. These factors contributed to much better payback periods than estimated in the 2004 demonstration of the VSD. Since the field demonstration in 2004 and publication of its results, the industry has quickly adapted, and VSD use in data centers has gained widespread acceptance. Some California electric utilities even started offering pilot programs as early as in 2007, with incentives to retrofit existing data centers with VSDs for better airflow management. The equipment manufacturers are also now offering "retrofit kits" to install VSDs and controls. Although some control schemes are not as efficient as others, these still provide significant savings.

The use of VSDs must be coupled with proper airflow management to prevent hot spots in data centers. A good airflow management also requires separation of the hot and cold airflows within a data center to prevent recirculation of hot air back to the ICT equipment. A physical barrier for separation of the hot and cold air is expensive and often impractical in a retrofit environment. The use of a distributed network of temperature sensors at the inlet of the ICT equipment could identify where hot spots, are and the information could be used to provide selective and localized barriers to prevent mixing, as well as control the speed of fans for management of airflow. In a 2008 retrofit installation of VSDs by Federspiel Controls (now renamed as Vigilent Controls) in Redwood City, California, distributed temperature sensors at the inlet of the ICT equipment with a wireless network were used to adjust the speed of the fans to maintain the air temperatures within acceptable ASHRAE conditions. This installation with six chilled water CRAC units demonstrated that the fan speed could be effectively controlled without the need and considerable expense of barriers for separation of hot and cold air; the fan speed automatically adjusted to account for some mixing. Fan speed was able to be reduced to about half, resulting in over 80% fan power savings (just 0.95 to 1.05 kW versus ~5.5 kW at full speed) to provide a cost effective solution with a payback period of less than a year after utility incentives; the payback period would have been more than four years with the cost of elaborate separation of hot/cold air and would not have met cost effectiveness criteria.

The savings potential in smaller data centers that typically use DX units rather than chillers is even more. Instead of six, seven, or more units in larger data centers, smaller data centers have two, three, or four CRAC units. Therefore, the redundant capacity could be 25, 33, or 50% and even more when actual ICT equipment load versus design load is considered. It is conceivable that the combined load from such a smaller data center with DX units exceeds the loads from large data centers with chilled water units.

The use of VSDs with chilled-water CRAC units is now well accepted in the industry. Extending the use of VSD on DX CRAC units is the next logical step, which was demonstrated in this project.

CHAPTER 2:
Varying Airflow with DX Air Conditioning Equipment and Use of Variable Speed Drives

2.1 The Market for DX CRAC Units

There are several reasons that small to midsize data centers use DX cooling equipment. Primary among these are costs and unavailability of efficient chillers in small sizes. Generally, DX cooling systems dominate in data centers with less than 500 kW of ICT capacity, and compete effectively with chilled water systems to 1,000 kW or more. Secondly, DX systems are modular in nature and can be added incrementally as data center capacity grows. This is an important consideration for companies. Many owners, concerned about initial costs and uncertain about business needs, start with building small data centers and expand capacity as business grows over time and prefer to use modular systems. Third, some data center owners do not like to see water or fluid in data center space and avoid chilled water systems. Fourth, modularity of DX systems also offers speed to market with low initial cost. Lastly, DX systems can also be more efficient because there is no intermediate heat exchange fluid such as water between the refrigerant and the air.

There are, however, some limitations and disadvantages in using DX systems; it is difficult to leverage cooler outdoor ambient conditions unless the site allows use of an air side economizer. Some of the reasons why chiller-based systems are preferred for larger data centers are from an energy efficiency standpoint, some large water cooled chillers offer higher efficiencies, and water side economizing capabilities can easily be used for cooling. A DX system can be either air cooled or water cooled for rejecting heat to the ambient air. An air cooled DX system directly rejects heat to the outdoor ambient air. It generally comes in two sections. The indoor section contains the refrigerant coil for cooling the data center space. The second section is located outdoors and contains a condenser for rejecting heat to the ambient air. The indoor section has a fan, typically constant speed, and the coil may be circuited to allow connection to one or two compressors to allow some capacity variation in cooling load. The refrigerant compressors are generally placed within the outdoor condensing unit section. The two sections are connected together with a pair of refrigerant pipes. The distance between the indoor and outdoor sections is generally kept small to reduce losses in the refrigerant pipes and for the system to work efficiently.

A DX system can also be water cooled. In a water-cooled system, indoor heat picked up from the space by the refrigerant moving through the cooling coil is rejected from the condenser coil to an intermediary fluid, which in turn rejects heat through a dry cooler or a cooling tower located outdoors. Water cooled DX units can be placed father away from the outdoor section than the air cooled DX units. Water cooled units may also have some glycol in the loop in cold climates to prevent the circulating water from freezing.

The use of VSDs on DX units does pose some additional challenges. In particular, when airflow rate is reduced, the cooling coil temperature in a DX unit is also reduced thereby allowing more

moisture to be condensed. Because cooling load in data centers is sensible only, any dehumidification causes extra energy consumption. After initial removal of more moisture with a lower cooling coil temperature and a corresponding reduction in the relative humidity of the space, there will be no additional moisture to condense because there is no generation of latent load in a data center. The second often-cited concern is that if airflow is reduced too much, the cooling coil temperature can fall low enough to cause the condensate on the coil to freeze. First, the airflow can be controlled in a manner that will avoid such low temperatures. Second, should condensate freeze on the coil, it is freezing outside of the coil and will defrost when the compressor stops. It does not harm the unit in any way. For example, the refrigerators at home routinely form frost on their cooling coils without causing harm to the compressor. Compressor controls can also be reset to cut off the compressor on low temperature and low pressure.

Resistance to the use of variable speed fans in data centers has mainly been driven by the fear that variable speed operation of data center cooling may adversely affect reliability. These concerns have been well addressed by the industry in the last two decades; office air conditioning equipment with variable air volume DX rooftop units is now common. The vendors are developing new CRAC equipment with compressor capacity modulation where fan speed can be varied.

However, there is a very large installed base of DX CRAC units that still have a long useful life remaining and could benefit from use of VSDs. Because the indoor CRAC units are operating in conditioned environment, their service life would be very long, much longer than the typical 15 years of the outdoor units. Therefore, retrofit solutions are needed to address the existing large installed base, which by some estimates is larger than 50% of the total cooling capacity in the data centers.

Until recently, there was a similar concern about the use of variable speed fans on chilled water-cooling units in data centers. However, these concerns have been overcome by recent successful deployments, and it is now widely accepted to have VSDs on CRAC fans as best practices.

2.2 Airflow in Cooling Equipment

DX CRAC equipment is designed with well-matched components that include a compressor, a cooling coil, a fan that moves air over the cooling coil, an air or water-cooled condenser, and a refrigerant expansion device. All components are selected to work efficiently within a specific operating range and may fail to work if operated much outside that range, although many safety devices are built in the system for it to safely shut down without catastrophic damage when it encounters conditions that are outside of its operating range.

Data center DX CRAC units generally have two compressors, each one with its own independent refrigeration circuit, including a cooling coil, condenser coil, and expansion device. Sometimes the cooling coil or condenser is shared in a physical structure but still has independent refrigeration circuits. The cooling coils can be totally independent pieces of hardware or a single piece of hardware with two totally independent refrigeration circuits. A single piece of hardware with independent but intertwined refrigeration circuits can help in efficiency at partial load.

Most of the current air-conditioning equipment used in data centers has been derived from the comfort air-conditioning designs for use in comfort conditioning of room spaces. A typical configuration of a DX CRAC unit uses three- or four-rows deep finned cooling coils that produce supply air temperatures in the upper 50s or low 60s degree Fahrenheit and allows delivery of airflow in the range of mid 400 to low 600 cubic feet per minute (cfm) per ton of cooling. This translates to about 125 to 175 cfm per kW of cooling capacity at full capacity. The design typically cools the air temperature by about 20°F across the cooling coils at full capacity. The cooling capacity of each refrigeration circuit is fixed. It provides cooling in discreet capacity steps; either its compressor is running and producing cooling or it is shut down and not producing any cooling.

Having two individual independent circuits allows for some cooling capacity modulation, although in discreet steps, at partial load to better match the cooling load. However, the fan speed does not modulate. Therefore, if one compressor is turned off, only 50% of the total cooling capacity is available although the airflow is still at 100%. The resulting temperature drop across the cooling coil is about half. When both compressors shut off, warm air circulates without cooling.

2.3 Reducing Excess Airflow

It has been proven that reducing excess airflow improves energy efficiency.[3] This not only reduces fan power requirement but can also help reduce hot spots and other problems related to excess airflow. Excess airflow results in unproductive use of fan energy. Reducing airflow will provide significant direct fan energy savings as well as indirect cooling energy savings from avoided fan heat losses. In existing data centers, reducing airflow can release spare cooling capacity that was earlier tied up in inefficient airflow to allow future additional ICT equipment to be installed in the data center.

Reducing airflow is easier said than done. Airflow management is critical in proper and efficient functioning of a data center. It can be done in a non-disruptive manner to the ICT equipment. It can be accomplished by preventing supply air leakage around cable cutouts and through racks with missing blanking panels, curtailing or eliminating cold air short circuiting back to the CRAC unit and other good housekeeping practices. Hot air containment and preventing it from mixing with the cold air that is entering the ICT equipment prevent hot spots and allow the airflow to be further reduced because most of the data centers are over provisioned with excess cooling capacity. The air containment can be based on individual racks (such as individual racks with chimneys) or complete aisles (cold aisle or hot aisle).

Once the need for the airflow is reduced, there are two ways to cut down on the airflow:

1. Turning off CRAC units
2. Reducing airflow through CRAC units

[3] *Airflow Management: Energy Efficiency Opportunities in Data Centers.* EPRI, Palo Alto, CA: 2011. 1021973

Turning CRAC units off is perhaps the most cost effective approach. One just needs to identify which units to turn off. It can be done by turning off one unit at a time and observing the temperatures within the data center. Care has to be taken that the unit being turned off is maintained in a "hot standby mode" so that in case any other operating unit fails, the hot standby unit picks up and provides continuous cooling.

2.4 Reducing Airflow in DX CRAC units

Reducing airflow through DX CRAC units can be done but it requires special attention. Various components and subsystems of a DX refrigerant system are fine-tuned to work in unison under all operating conditions and any changes in operating conditions will permeate through the system that may affect its performance under the new operating conditions. If operating conditions drift out of range, the system's safety devices either shut it down or the system breaks down. There are obvious concerns to safe and efficient operation of the system, but many of the concerns are often blown out of proportion. These concerns and scientific response to the same are presented below:

2.4.1 Potential of Condensate to Freeze on Cooling Coil: Not True

When less air flows over a cooling coil while the compressor is operating at full capacity due to a lack of capacity modulation, the coil temperature tends to drop to a lower than normal level further cooling down the air flowing over it. Depending on the inlet air humidity, the lower temperature may result in condensing more moisture on it. Normally, the condensate from the coil eventually runs down the drain. If airflow continues to be lowered, however, the cooling coil temperature will fall further and the condensate may freeze on the cooling coil and block airflow.

Because high latent heat loads are not generally found in data center spaces, most DX systems intended for this application are designed in such a way that they do not unnecessarily dehumidify the air, which requires the cooling coil to operate at as high a temperature as possible but just cool enough to dehumidify for maintaining acceptable indoor humidity levels in humid climates. Under these design conditions, it has been found that the airflow rates per ton of cooling are quite high. Even if the airflow rates are reduced down to 60% of the rated airflow, the cooling coil temperature does not reach at low enough levels for the condensate to freeze. But at 60% of design airflow, fan power is reduced to just about 22% of the rated fan power draw, providing 78% fan savings. Because the fans run continuously, data centers generally have much more airflow than needed, and fan energy savings can provide significant energy efficiency advantages.

In fact, when contacted, the leading DX CRAC unit manufacturers provided ratings that showed safe operations of units down to 60% of the rated capacity in data center applications where return air temperatures are generally high.

2.4.2 Potential Lower Energy Efficiency at Lower Airflow Rates: Not True

At lower airflow, the cooling coil temperature is lowered and the compressor has to work harder to remove heat, and it could be argued that this will reduce the cooling energy efficiency. It is true that the compressors have to work harder and use more power. However,

the reduction in fan power energy more than offsets any increase in compressor power. The data in Figure 1 and Figure 2 confirm that the unit's seasonal energy efficiency ratio (SEER) increases as fan speed is reduced.

2.4.3 Potential Mechanical Failure at Low Airflow Rates: Not Likely

There is a fear of potential mechanical failure of the DX CRAC units if you run at lower fan speeds and airflow rates. It is likely that some units could run into issues when their filters are dirty and reduce airflow even more, or airflow is blocked with some obstructions, but most DX CRACs have built-in safety controls—such as minimum airflow cutout and low refrigerant/temperature cutout—that protect the units.

The Electric Power Research Institute (EPRI) tested two air cooled DX CRAC units and two water cooled DX CRAC units from two different manufacturers in a project funded by the California Energy Commission over a two-year period in two operating data centers in California with speeds as low as 60% without any issues. Of course, it is always good to exercise precaution and use best practices, such as making sure that filters or other obstructions are not blocking airflow and the data center return air temperatures are not very low.

2.4.4 VSDs on DX CRAC Unit Fans: Yes!

Airflow in a DX CRAC unit can be reduced several ways, such as blocking air flow, changing motor pulley size, or varying the fan speed by installing a VSD on the fan motor. Because the ICT load in a data center would vary over time, it is preferable to install a VSD so that the fan speed can be easily adjusted as requirements change over time.

2.4.5 Manual or Automatic Control of VSD: Either Way it Saves Energy

Should you control the VSD manually or use automatic control system? Either one will save you energy. It will depend on user preference. It is possible to manually adjust VSD speed so that hot spots are eliminated or reduced. It may be necessary to adjust the speed periodically as data center ICT loads change or when airflow adjustments are needed.

Automatic controls for VSD can provide comfort in knowing that the data center is being continuously monitored and the system may respond automatically to ICT load changes or failure of any of the DX CRACs. Some vendors offer wireless sensors spread across the data center that monitor ICT equipment inlet temperatures and analyze the data to send commands to the CRAC units' VSD to adjust fan speed optimally. Continual operational optimization may yield some additional energy savings.

2.4.6 Containment: Optional

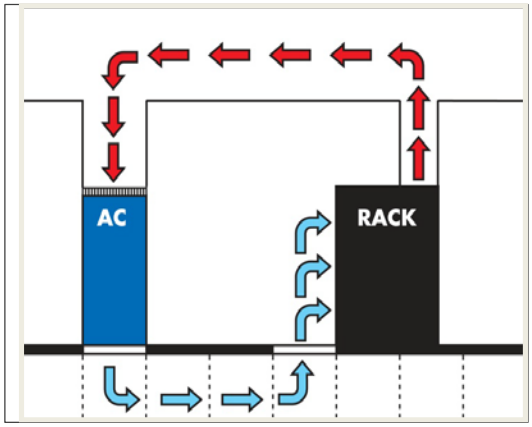
Is containment needed with the use of VSDs on CRACs? Not necessarily. But if containment is used, VSDs are necessary. Among two sites where EPRI conducted field demonstration with VSDs on DX CRACs, one site did not have any containment while the other had it. Both systems saved energy. The amount of energy savings depended upon how low a fan speed at which the ICT load is satisfied or the minimum acceptable fan speed in DX CRAC units, which is typically 60% or 67% (2/3rd the rated fan speed). In one of the EPRI test sites, the fan speed was gradually reduced until it reached the lower limit of 60% without requiring any containment, so no

containment was done. The other site already had flexible strip curtain for hot air containment with over-the-plenum return air back to the CRAC units.

Containment—cold aisle, hot aisle, or rack—requires that the airflow quantity from the CRAC units must match the airflow quantity over the ICT equipment racks. This necessitates the use of VSDs on the CRAC unit fans. Because the airflow in the ICT equipment, especially new ones, can vary over time, and the total load of the ICT equipment can also vary over time, the CRAC units must have the ability to vary the airflow to provide the amount needed by the ICT equipment racks at all times.

The use of variable airflow in conjunction with containment was first demonstrated in a large enterprise data center by Oracle in 2004.[4] Individual rack containment was used as shown in Figure 5. Until this demonstration, the industry was skeptical about using variable airflow in data centers. The CRAC units in the Oracle application were chilled water based and did not have the additional issues as are identified with DX CRACs here, but the argument for using the VSDs on CRACs is still valid.

Figure 5: Schematic and Picture of Individual Rack Containment



As containment became popular, some data centers have used it without adding variable-airflow capacity in their CRAC units. Without this, there is no path for excess airflow to find its way back to the CRAC units. This causes greater pressure differential between the hot and cold aisle. If the barrier uses strip curtains, the excess airflow will find its way through small openings where strips of curtain overlap as shown in Figure 6. The use of a barrier may have reduced the hot spots, but it would not provide energy savings. The energy savings are realized only by slowing down the fan speed.

Care should be taken when installing containment material because of the possibility of blocking the planned operation of the sprinkler system. The authority having jurisdiction,

[4] *High Density Heat Containment*, ASHRAE Journal, p.38, Dec. 2007

usually the City Fire Marshall or City Building Inspector, must be contacted to approve any proposed containment system.

Figure 6: Importance of VSD on Cooling Equipment with Containment

CHAPTER 3: Field Demonstrations

3.1 Methodology

Under this project funded by the California Energy Commission, EPRI conducted field demonstration at two small data centers with VSDs on DX CRACs. Each site had two DX CRAC units with 100% redundancy, which is typical of small data centers. VSDs on existing DX CRAC units' air distribution fans were installed. There were no other changes made to the DX CRAC units. The manufacturers of the DX CRAC units, Liebert and Comu-Aire, were contacted, and they provided the DX CRAC unit performance data under different indoor airflow rates down to levels where the units could operate safely. The manufacturers indicated the minimum refrigerant temperatures in cooling coils below which it would not recommend units to operate. The minimum fan speed when refrigerant temperature reached the minimum acceptable levels varied, of course, by the indoor air temperature and humidity as well as outdoor ambient temperature in the case of the air cooled DX CRAC unit and condenser water temperature in the case of the water cooled DX CRAC units. The manufacturer's data indicated that we could run the units down to 60% of the rated fan speed in our application without running into minimum refrigerant temperature issues.

The DX CRAC units were operated with fan speed control under two different modes of operation: 1) manual fan speed settings and 2) use of an automatic control system that monitored air inlet temperature to the ICT equipment and used the temperature data to vary the fan speed. In the manual mode, the fan speed was set from 100% to 60% in steps of 10%. In the automatic control system, a minimum fan speed was set at 70% and later at 60%. Vigilent provided the automatic control system that used a number of wireless temperature sensors at the inlet of the ICT equipment and were distributed throughout the data center. The temperature data from theses sensors were communicated to a server that processed and analyzed data and calculated the desired fan sped and sent control signals to the CRAC unit fan's VSD for speed control. Power use, energy consumption, and temperature data were recorded at three levels: manually, through building management and control system, and from the automatic control system. The data were analyzed for system performance and energy efficiency.

The demonstrations covered a wide range of possible DX system configurations available in the market. One site had air cooled DX CRAC units while the other had water cooled DX CRAC units. Each CRAC unit had two compressors and two refrigeration circuits. The air cooled CRAC unit had an inter-twined cooling coil configuration, while the water cooled CRAC unit had independent coil sections.

The units were retrofitted with VSDs and operated for more than a year. The VSDs were initially controlled manually and worked fine. Automatic controls were later installed to test its effectiveness as well as to collect additional systems' performance data. The automatic control systems also worked as expected.

3.2 Demonstration Sites Description

The salient features of each site are provided below:

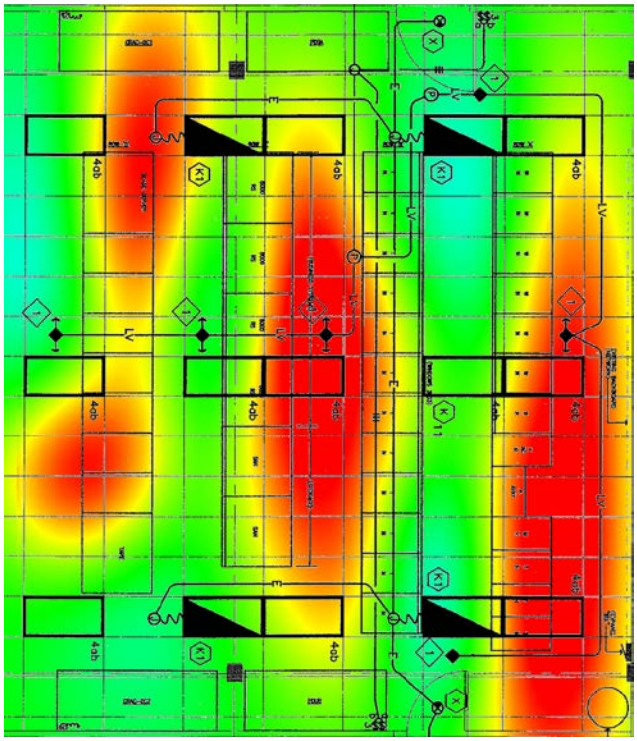
3.2.1 EPRI Data Center

EPRI has a small data center at its headquarters facility in Palo Alto, California, that is served with two air cooled DX CRAC units. The site offered many advantages, including proximity to the researchers, and its IT and facility operations teams agreed to participate in the demonstration project. The salient characteristics of the site and its mechanical cooling system are outlined below:

- Data center size: ~1300 square feet
- ~12-years-old equipment
- ~90 kW of ICT equipment load
- Raised floor
- Underfloor air distribution with air return direct to CRAC units in the room; return air opening at the top of CRAC units
- No hot air or cold air containment
- Cable cutouts and other miscellaneous slab cutouts to accommodate conduits, UPS, and CRAC units that allowed cold air to bypass without moving over the ICT equipment
- Underfloor power distribution
- Air-cooled DX CRAC units
- Liebert Model DH 380AA; 30 tons nominal capacity
- Fan motor size: 10 HP
- Compressors located in the indoor CRAC unit; air cooled condenser located on rooftop
- Two compressors in each CRAC unit; capacity steps: 0%, 50%, and 100%
- Two independent refrigeration circuits
- Intertwined cooling coil configuration

A schematic of the EPRI data center layout is shown in Figure 7. The schematic also shows a thermal map of temperatures in the data center that was obtained from the Vigilent automatic control system using wireless temperature sensors located at the inlet of the ICT equipment. The blue, green, yellow, and red colors progressively show cold to hot temperatures within the data center space.

Figure 7: Thermal Map Showing Temperature Distribution in EPRI Data Center



3.2.2 NetApp Data Center

NetApp offered a small data center/ICT lab at its Sunnyvale, California, campus for participation in this project. This site also offered several advantages such as water cooled CRAC units, a different manufacturer from the units used at the EPRI data center, and proximity to the researchers. Other salient features of the data center are:

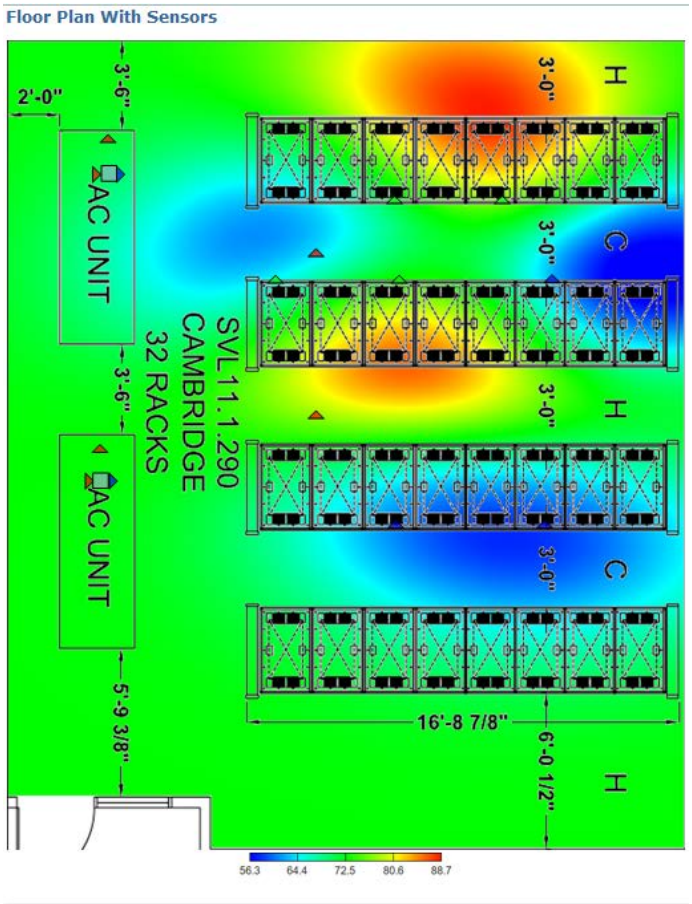
- Data center size: ~1000 square feet
- >10-year-old CRAC units (that were reused in a 2-year-old data center/ICT lab)
- ~55 kW of ICT equipment load
- CRAC units on slab (no underfloor)
- Overhead supply air distribution and return air through overhead plenum
- Strip curtains from ceiling to racks for cold air containment
- Overhead power distribution
- CRAC unit model Compu-Aire CAW 2034; 20 tons cooling nominal capacity
- Indoor fan motor: 7.5 HP
- Water-cooled DX CRAC units, compressors located in the CRAC unit

- Remote cooling tower with an intermediate heat exchanger to keep condenser water separated from the open loop cooling tower water
- Two compressors in each CRAC; capacity steps: 0%, 50%, and 100%
- Two independent refrigeration circuits
- Independent cooling coils sections

A schematic of the NetApp data center layout is shown in

Figure 8. The schematic also shows a thermal map of temperatures in the data center that was obtained from the Vigilent automatic control system using wireless temperature sensors located at the inlet of the ICT equipment. The blue, green, yellow, and red colors progressively show cold to hot temperatures within the data center space.

Figure 8: Thermal Map Showing Temperature Distribution in NetApp Data Center



3.2.3 Significance of Refrigerant Circuiting in DX CRAC Units

The refrigerant circuiting in a cooling coil can play an important role in its operational efficiency. In each of the air cooled or water cooled DX units, each compressor had its own independent circuit. An independent circuit allows an optimized performance match between individual cooling coil and compressor over a wide range of operating conditions and eliminates concerns of proper refrigerant oil return from the cooling coil to the compressor at partial load operation. Each of the air cooled and water cooled CRAC units had independent refrigerant circuits for each of its two compressors. The refrigerant circuiting within a cooling coil also plays an important role in the determination of the unit performance. In an intertwined refrigeration circuit, the two independent refrigeration circuits are intertwined within a single cooling coil. Therefore, the refrigerant from each compressor circulates through the entire cooling coil, and the entire cooling coil surface area is actively providing cooling even when only one compressor is operating. This improves energy efficiency of the refrigeration system at partial load. However, it does allow the cooling coil surface temperature to be slightly warmer, which condenses less moisture from the air. This is a preferred approach where lower humidity levels are not required. In independent coil sections, the total cooling coil is split into two sections, and the refrigerant from one compressor circulates through its own section of the cooling coil. Each half of the cooling coil provides active cooling when its associated compressor is operating. The energy efficiency of the refrigeration system remains the same at partial load when only one compressor is operating. However, because the cooling coil temperature does not change, it does not change its moisture removal capabilities. It is a preferred approach when lower humidities are desired.

The demonstration project, however, provided an opportunity to test a wide range of the CRAC unit designs as well as a wide variation in its application, which would cover a majority of potential applications in the field.

CHAPTER 4:
Results and Discussion

The DX CRAC unit manufacturers provided performance data of the CRAC units under different airflow rates, which are included in the appendix of this report. The energy efficiency data at different airflows were analyzed, and a summary is presented in Table 1 for the EPRI DX CRAC units. Figure 9 and Figure 10 show only the SEERs of the Liebert air-cooled DX CRAC units at EPRI at 100% and 50% cooling capacities for return air conditions of 75 and 62 degrees Fahrenheit dry bulb and wet bulb temperatures in order to keep the plots legible. An energy efficiency ratio (EER) is defined as the ratio of the total cooling capacity (in Btu/h) divided by the unit's power requirement (in watts). The SEER is defined as a ratio of the sensible cooling capacity divided by the power consumption. The power requirements include compressor power, outdoor condensing unit power, and the indoor CRAC air distribution power.

Observations of these figures clearly show that both the total and sensible cooling SEER increases as fan speed is reduced. Although cooling capacity reduces slightly at lower fan speeds, the combined fan and compressor power reduces much faster due to the cubic relationship of the fan laws, yielding overall EER and SEER improvements. An SEER improvement of 20% to 39% is observed while reducing fan speed from 100% to 67% at 100% compressor capacity. The improvement, however, is even larger, from 22% to 47%, at partial load operation at 50% capacity with only one compressor in operation. The relative improvement in energy efficiency reduces when fan speed is incrementally lowered. This is partly due to the fact that the cooling coil effective temperature reduces when fan speed is lowered, which lowers vapor compression system energy efficiency, and the unit would provide some extra latent cooling. However, because there is no generation of moisture in the data center space, the space humidity is soon pulled down to levels where no more moisture removal is needed, and the unit provides primarily sensible cooling.

Table 1: Seasonal Energy Efficiency Ratio under various conditions

		Indoor DX CRAC Fan Speed (Liebert Model DH 380AA)									
		100%		90%		80%		70%		67%	
Capacity	Ambient Temperature Deg F	Total SEER	Net Seasonal SEER	Total SEER	Net Seasonal SEER	Total SEER	Net Seasonal SEER	Total SEER	Net Seasonal SEER	Total SEER	Net Seasonal SEER
100%	95	11.8	9.3	13.0	11.2	14.0	11.9	14.9	12.4	15.1	12.5
	80	13.7	10.4	15.3	12.7	16.5	13.7	17.6	14.3	17.9	14.5
	65	14.5	10.9	16.2	13.1	17.5	14.0	18.7	14.8	19.1	15.0
50%	95	6.6	5.3	7.0	6.6	7.2	7.1	7.4	7.5	8.0	7.7
	80	7.1	5.8	7.6	7.3	7.9	7.9	8.8	8.4	9.0	8.5
	65	7.3	5.9	7.8	7.3	8.2	7.9	9.0	8.4	9.3	8.5

Figure 9: Cooling Seasonal Energy Efficiency Ratio of a DX CRAC Unit versus Airflow

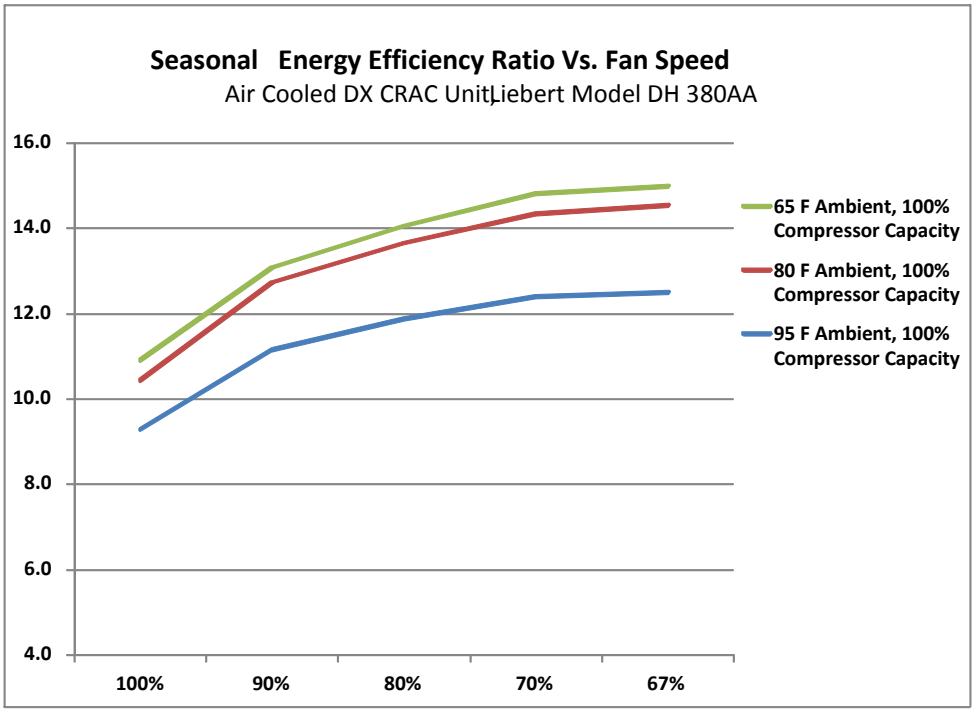
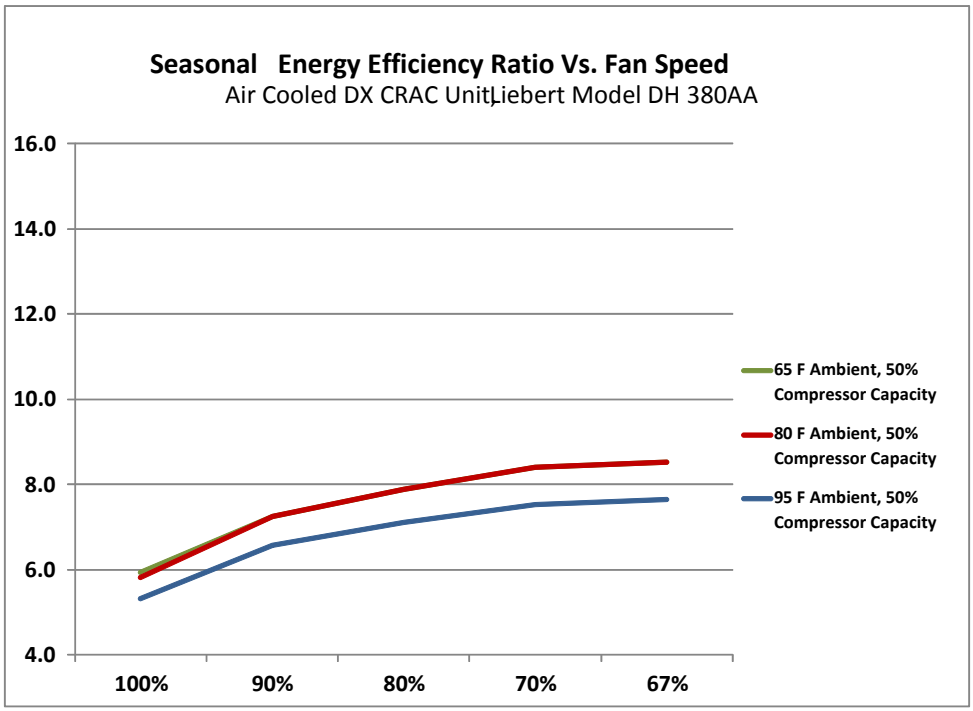
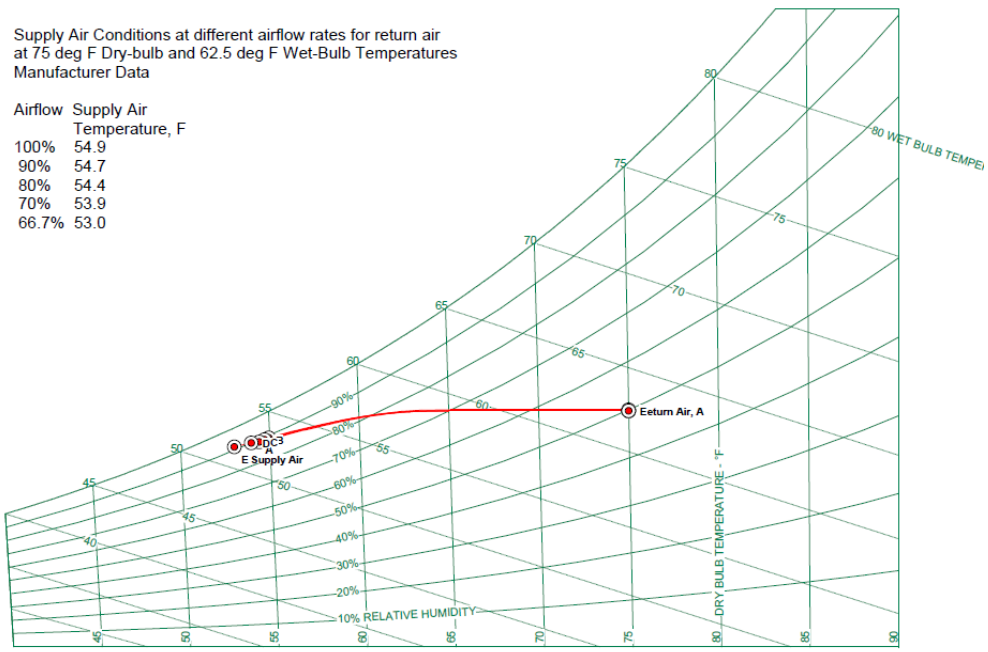


Figure 10: Cooling Seasonal Energy Efficiency Ratio of a DX CRAC Unit versus Airflow



Manufacturer's data for the supply air temperature of the water cooled DX units at NetApp at different airflow rates are plotted on a psychrometric chart in Figure 11. The data shows that the supply air temperature reduces from 54.9°F at 100% speed to 53°F at 60% fan speed. The supply air temperature is well above conditions where condensate water could freeze on the cooling coil. Generally, manufacturers are concerned about potential spot condensate freezing when average cooling coil temperatures fall below about 40°F or supply air temperatures fall below about 45°F.

Figure 11: Supply Air Temperatures at Different Airflow Rates in a DX CRAC Unit



4.1 EPRI CRAC Unit Performance with Reduced Fan Speeds

Figure 12 shows a quick snapshot of the return and supply air temperatures of both DX CRAC units as well as ambient temperature for a long period of six months from January 1 to June 30 2012.

The data show that the supply air temperatures were generally above 50°F, even when the return air temperatures were about 68°F, and ambient air temperatures fell below 40°F in January, 2012. On occasions, supply air temperature momentarily dips below 50°F to as low as 45°F. This is suspected to happen during manual servicing or fan speed resets.

Figure 12: Snapshot of the EPRI DX CRAC Unit's Performance

The occasional temperature drop below 50°F to as low as 45°F did not cause any issue with proper mechanical performance of the DX CRAC units. The concern often expressed for reducing fan speed in DX CRAC units is that the moisture might freeze on the cold refrigerant cooling coil. However, supply air temperatures as low as 45°F should not cause any alarm for moisture freezing on the cooling coil. Generally, supply air temperatures have to fall well below 40°F for the cooling coil to be cold enough to freeze moisture condensed on it. Incidentally, any moisture freezing on the cooling coil would restrict the air flow area on the coil, and that in turn would increase the air speed on the remaining coil area and help to reduce further freeze up. So, any amount of moisture that could freeze on the coil would have limited impact.

The DX CRAC units' performance for the EPRI demonstration site at different fan speeds is shown in Figure 13, Figure 14, Figure 15, and Figure 16. These plots shows outdoor, return, and supply air temperatures over 24 hours for the two CRAC units, CRAC A and CRAC B. These also show the times when the fan speed was reset to lower speed manually. The following observations from these charts are:

1. The compressors are frequently cycling in both CRAC units. Because the units are oversized, cycling is expected, but the frequency of cycling is rather high, which indicates that the thermal mass within the data center is relatively small.
2. In one CRAC unit (A), it looks like only one compressor cycles on and off, while the other does not turn on at all.
3. In the other CRAC unit (B), it looks like one compressor continuously stays on while the second compressor cycles on and off.
4. The supply air temperature drops 2 to 3°F when fan speed is changed from 100% to 90%.
5. The lowest supply air temperature in CRAC A drops from ~62°F at 100% fan speed to ~59°F at 90% fan speed.
6. The lowest supply air temperature in CRAC B drops from ~56°F to ~54°F.
7. Although the thermostat was not touched, notice that the room air temperature (measured at ~3 ft. high from the floor in between the racks and the CRAC) reduces from ~71°F at 100% fan speed to ~70°F at 90% for CRAC A. This would indicate that the CRAC units are providing more cooling at lower fan speeds.
8. At the lowest fan speed of 60%, the supply air temperature in CRAC B varies between low values of ~50°F when both compressors are on to ~58 F, when one compressor is operating while the return air temperature is ~65 to 67°F. The low supply air temperature of 50°F is well above the temperatures where risk of condensate freezing, if any, could occur.
9. The units ran at the lowest fan speed of 60% for extended periods of time over ~18 months without any issues.

Figure 13: CRAC Units Supply & Return Air Temperatures (EPRI)

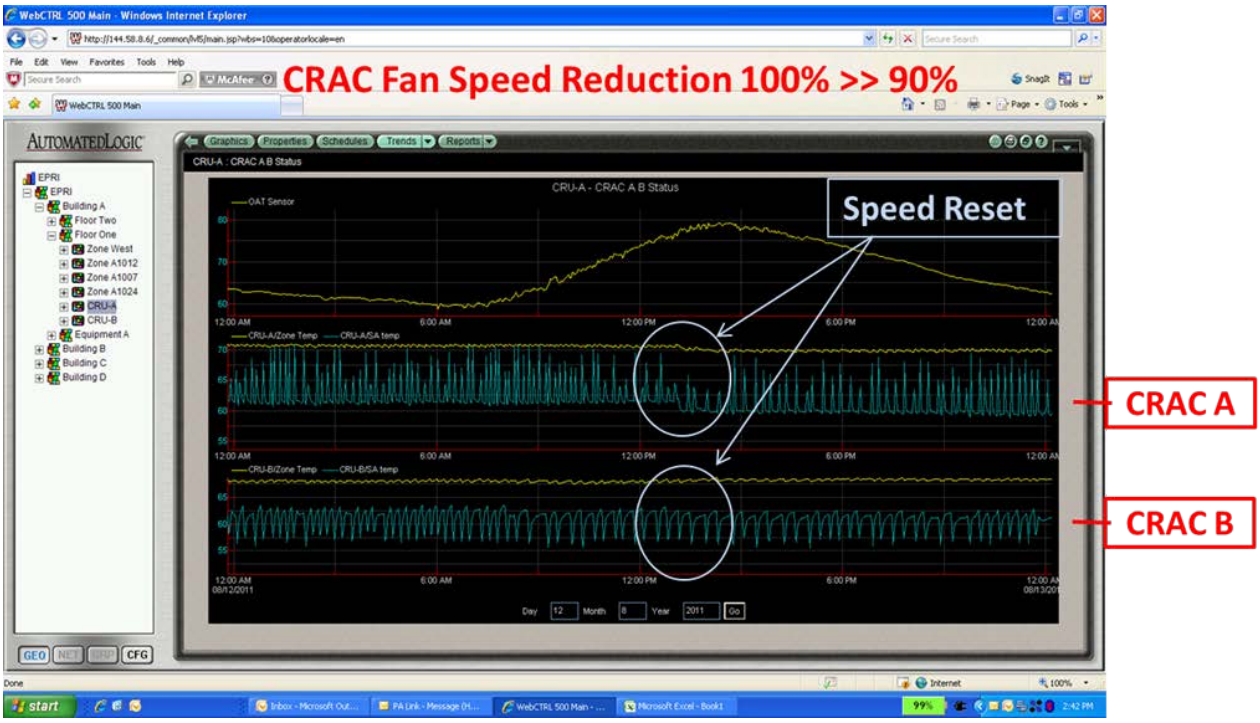


Figure 14: CRAC Units Supply & Return Air Temperatures 9EPRI)

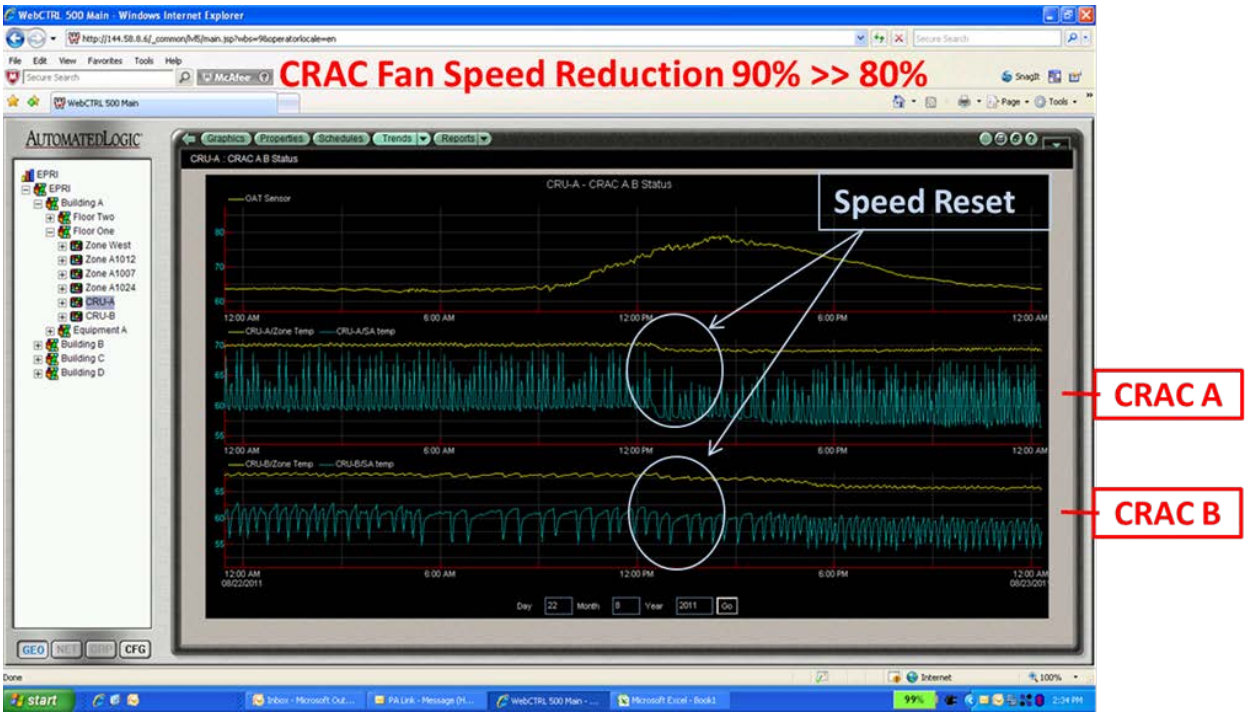


Figure 15: CRAC units Supply & Return Air Temperatures (EPRI)

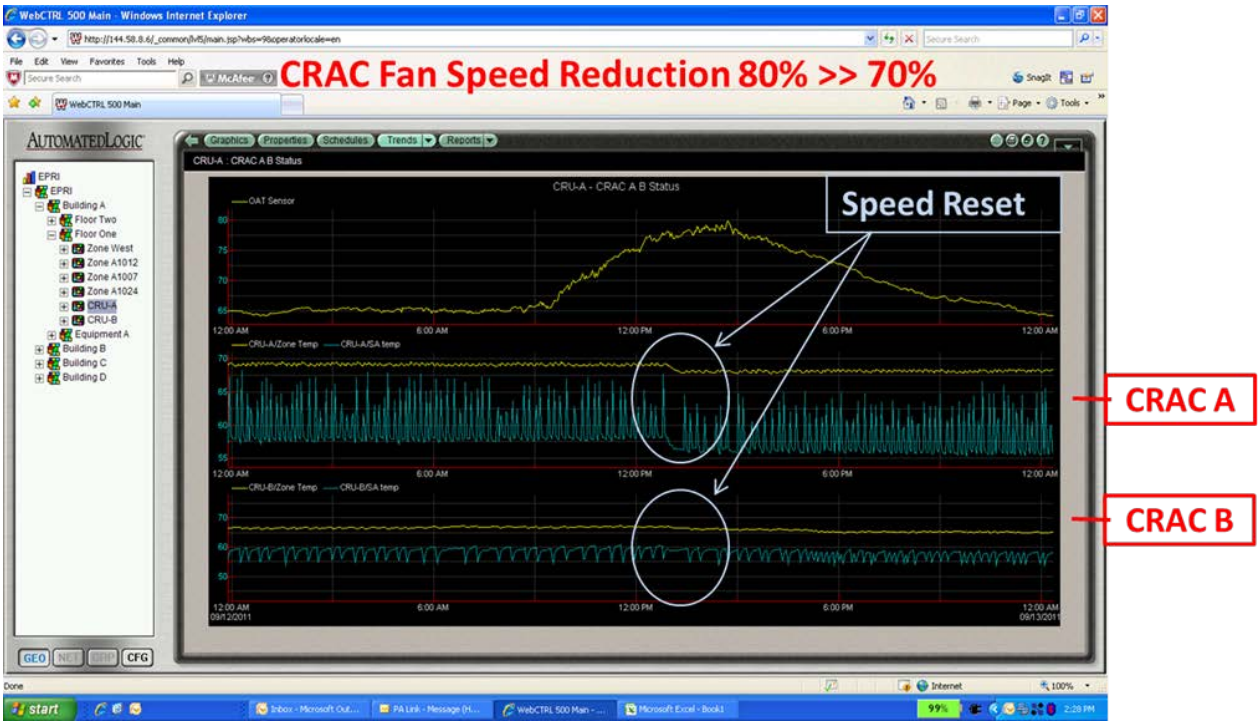
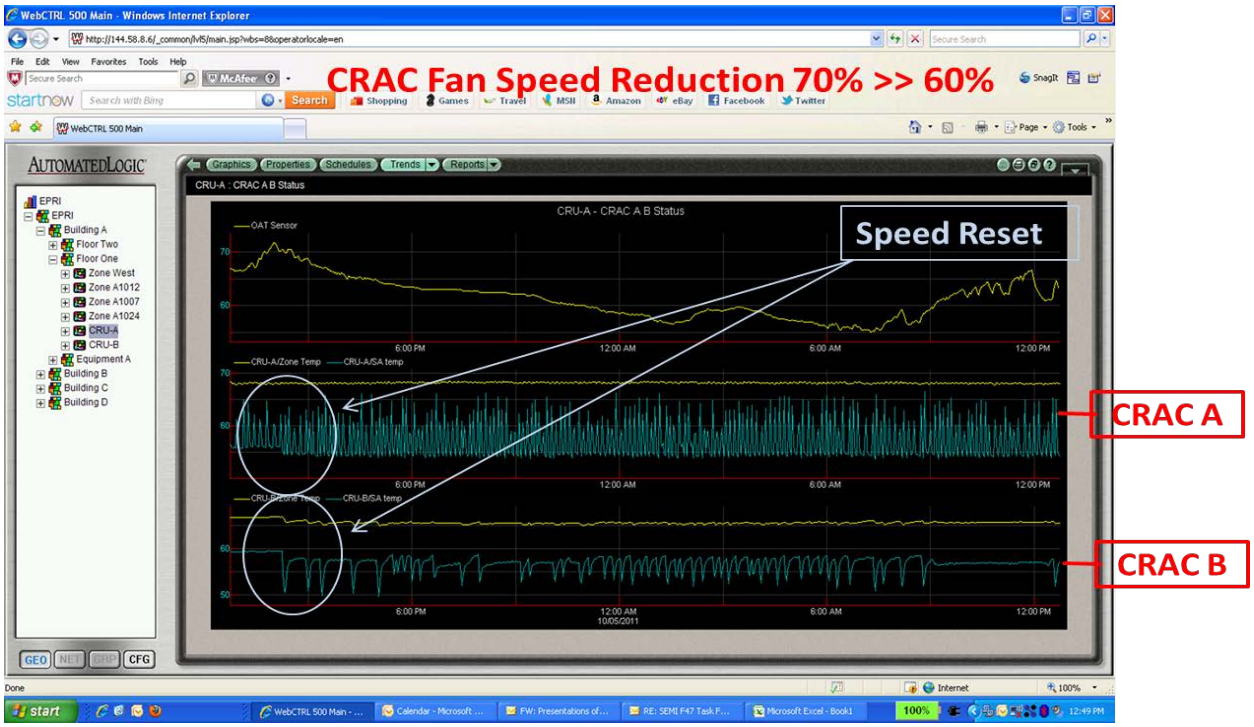
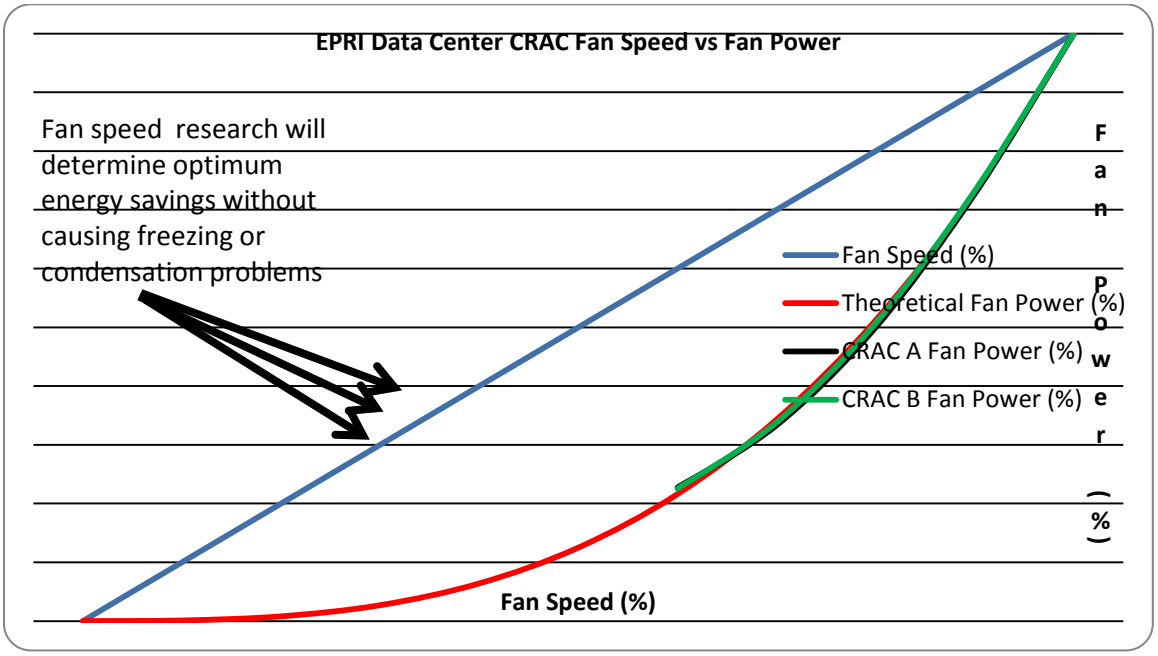


Figure 16: CRAC Units Supply & Return Air Temperatures (EPRI)



The fan power consumption at different fan speeds was measured and plotted in Figure 17. The data indicate that the fan power in this installation followed the relationship established by the Fan Affinity Law closely. Power use by the two CRACs, A and B, and theoretical power use based on the Fan Law overlap on the chart.

Figure 17: Measured Fan Power at Different Fan Speeds at EPRI Installation

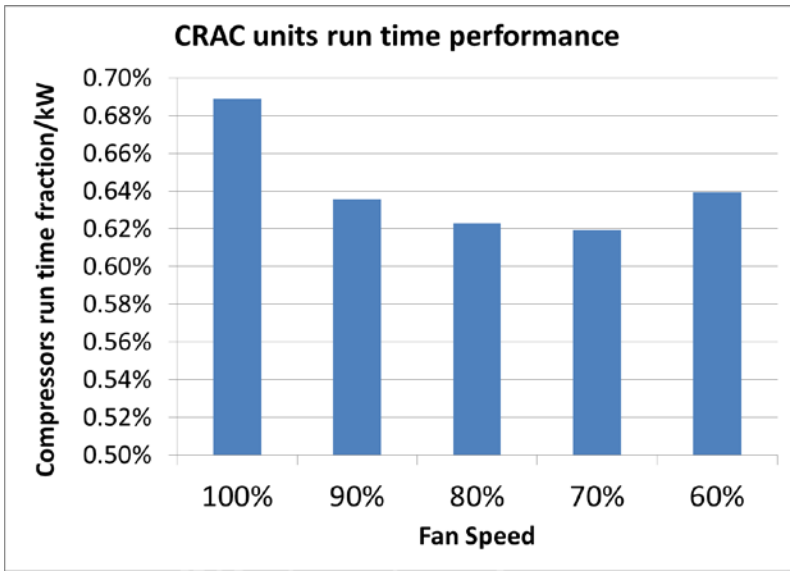


4.2 Compressor Run Times at Reduced Fan Speeds

The CRAC controls track accumulated number of hours that each compressor runs. These data were recorded manually before and after any changes to the fan speed before activation of the automatic controls. The fan speed was gradually reduced from 100% in steps of 10%. At each step, the system was operated for a week or longer until the operational staff was comfortable to go to the next step down in speed. There were no adjustments to the thermostat or any other controls settings.

A chart of compressor run time at different fan speeds is shown in a chart in Figure 18. As expected, when the fan speed is reduced, not only does the fan energy consumption go down, the compressor energy consumption should also go down. A proxy for compressor energy consumption, compressor run time fraction, per kW of the IT load is plotted in the figure. The compressor energy consumption reduced with fan speed reduction. Energy savings were derived both from fan energy as well as compressor energy as fan speed was reduced. These data are also presented in Appendix A.

Figure 18: Compressor Run Time Fraction versus Fan Speed



4.3 Energy Savings with Reduced Fan Speeds

The power use data by the ICT equipment as well as the cooling equipment (indoor CRAC fans, indoor compressors and outdoor air cooled condenser fans) were analyzed. The data for the EPRI site is presented below for the following conditions:

1. 100% fan speed under manual control (Cooling power at 100% = 54.0 kW)
2. 90% fan speed under manual control (Cooling power at 81.9% = 44.2 kW)
3. 80% fan speed under manual control (Cooling power at 80.3% = 43.4 kW
4. Fan speed controlled by Vigilent Automatic Controls with minimum fan speed set at 70% (Cooling power at 73.5% = 39.7 kW)
5. Fan speed controlled by Vigilent Automatic Controls with minimum fan speed set at 60% (Cooling power at 68.0% = 36.7 kW)

There are two DX CRAC units in this small data center with one provisioned as a redundant unit. Each of the two units is sized to serve the total load of the ICT equipment and it is expected that the units' fans will be capable of slowing down to the lower fan speed limit of 70% or 60%. However, it should still be available to ramp up to full speed and provide 100% of the necessary cooling if the other unit failed. This condition was also observed in the field.

Periods of data before and after adjustments to the fan speed were selected to compare the cooling energy requirements by the indoor fans, compressor, and outdoor condenser fans units. The indoor temperature settings were unchanged, but we did notice return air temperature rise with lower fan speed, possibly due to less mixing with cold air and more air stratification at lower flows. The outdoor weather data over the test periods before and after the speed

adjustments were small, and data were not corrected for the weather data. The internal ICT load varied very slightly—less than 0.4% over the test period.

The energy use by the ICT equipment and the cooling equipment is plotted in Figure 19 and

Figure 20 below. Total cooling energy reduction was very impressive: It ranged from 18.1% at 90% fan speed; 19.7% reduction at 80% fan speed; 26.5% reduction at a minimum fan speed set point of 70%; and 32.0% at the minimum fan speed setting of 60%, in comparison to the cooling energy use at 100%.

Figure 19: Energy Use by ICT and DX CRAC Cooling Equipment at Different Fan Speeds

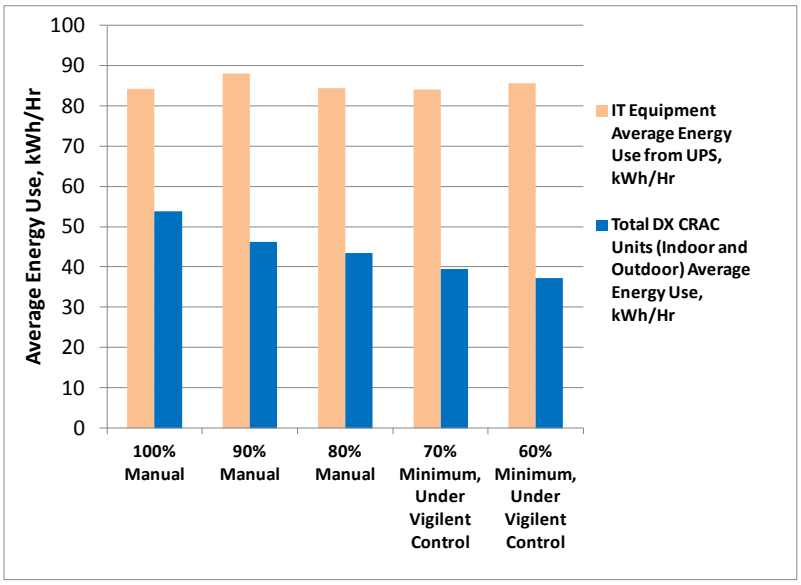
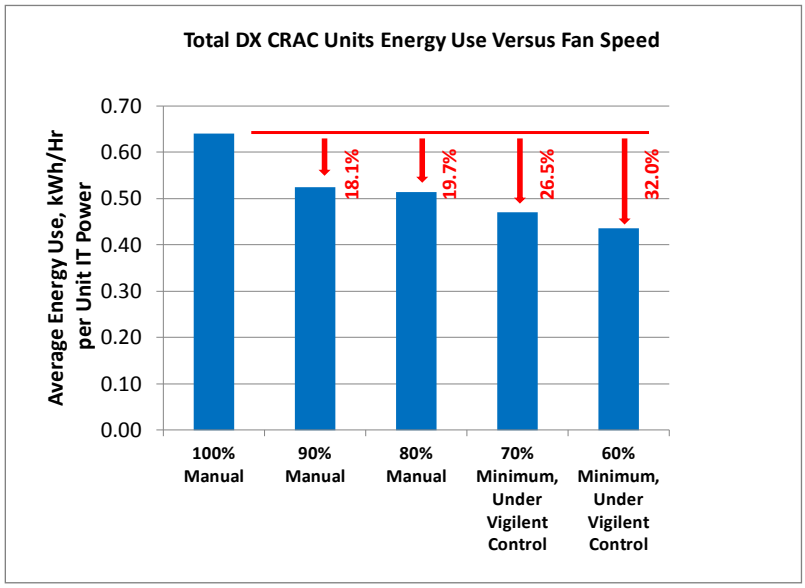
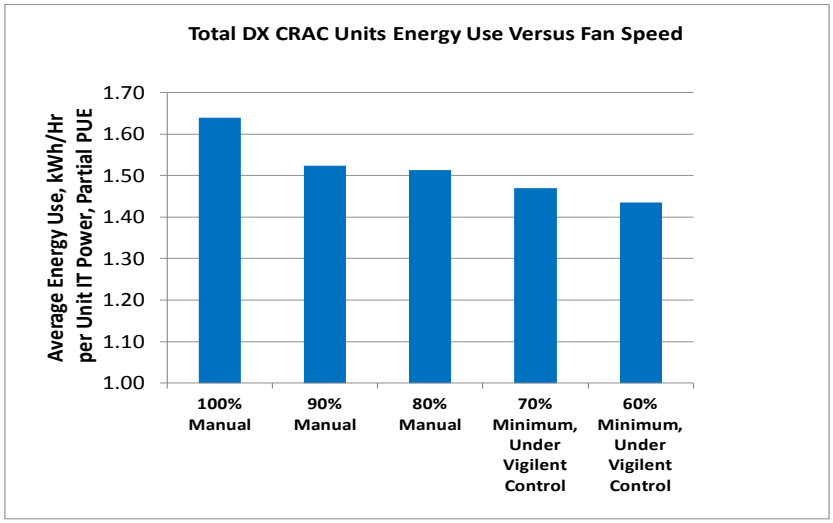


Figure 20: DX CRAC Unit Total Energy Use versus Fan Speed for Each Unit of ICT Power



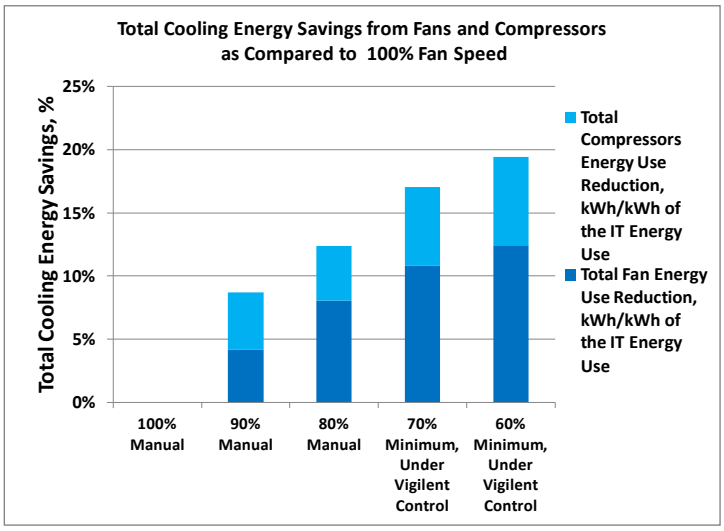
The cooling energy savings per unit of the ICT energy use, a measure of the absolute reduction in the PUE, were also very impressive and ranged from 0.087 at 90% fan speed to 0.194 at the minimum speed of 60%, as shown in Figure 21. Figure 21

Figure 21: Cooling PUE with DX CRAC Units at Different Fan Speed Settings



The contributions to energy savings from the fan and compressors are summarized in Figure 22. As expected, energy savings from compressors contribute about a half of the energy savings from fans, and the combined energy savings of 8.7% at 90% fan speed to 19.4% at 60%

Figure 22: Total Cooling (Fans and Compressors) Energy Savings at Different Fan Speeds

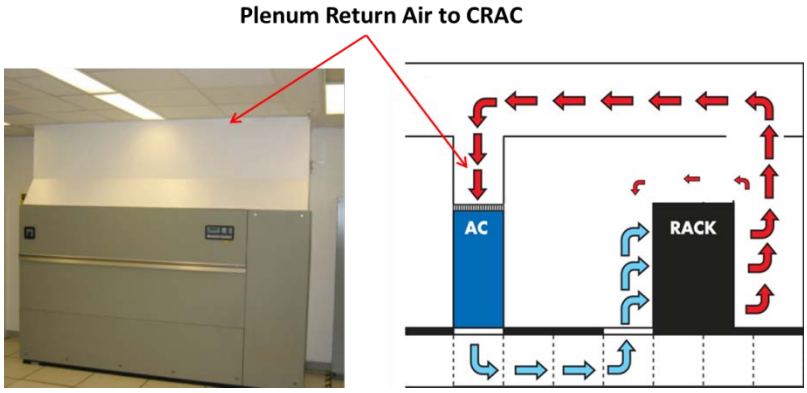


CHAPTER 5:
Indentifying Opportunities for VSDs in Retrofit Applications and Estimating Energy Savings

In a new system design, it is cost-effective to install variable-speed fans for airflow management, and it is becoming a common practice, although containment is not as prevalent. However, retrofitting existing data centers with variable-airflow devices and containment can be a challenge. In this section, we will discuss how to identify energy savings opportunities through good airflow management in existing data centers and offer some simple tips on estimating its energy-savings potential. These strategies and approaches are listed below and can be used successfully with DX CRAC units as well as chilled water CRAC units, which are sometimes referred to as *CRAH units.* However, any references to CRAC below refer to both DX CRAC and CRAH.

1. Though it is preferred, it is not mandatory to use containment when variable speed drive fans are used with CRAC. VSDs can be used on CRAC fans without using containment. Containment only helps in creating a physical barrier between hot ICT discharge air from cold supply air. It is often quite expensive to install, especially in retrofit environments, and creates physical barriers between hot and cold aisles. It may require reconfiguration of fire-suppression systems that can be prohibitively expensive. However, as long as hot spots can be prevented or limited, there will still be savings from installing VSDs. One way to limit hot spots would be to use a return duct from a plenum to the CRAC units and direct all return airflow through the plenum, as shown in the schematic and picture below in Figure 23. This will reduce short cycling as well as reduce hot spots.

Figure 23: Direct Plenum Return to Reduce Hot Spots and Short Cycling



2. VSDs can be easily installed on CRAC unit fans. In DX CRAC units, limit the lower fan speed set point of 60% or higher. There are a few items to take into consideration while considering VSDs for CRACs. The VSDs should be placed within a short distance from the motor to avoid power harmonics. This is generally not a problem if the VSD is located within 10 to 15 feet from the motor, which is common with CRAC units. Moreover, VSDs are generally installed on VSD rated (inverter duty) motors, and many

of the older CRAC units may not have VSD rated motors. You do not need to replace motors when installing VSDs, as it would be an added expense. Some field experience has shown that it is not always necessary to upgrade the motor, and so the expense of replacing the motor can be deferred to some later date. VSDs generate eddy currents and heat in motors; however, because these motors are located in a cold air stream, potential damage from heat buildup is not an issue. The eddy currents, however, could cause pitting on the motor shaft over time, which may eventually need replacement, perhaps after several years. There will be, however, enough warning signs from the motor shaft grinding, and its service/replacement could be scheduled during maintenance. These eddy currents can be avoided with the use of inexpensive grounding brushes that create a path to drain currents from the motor shaft to the motor body.

3. Can VSDs be installed on CRAC fans? There are some issues with it, but the simple answer is "yes," with some caution. The use of VSDs had been limited to chilled-water CRAH units so far; but the recent study at EPRI funded by the California Energy Commission has shown that VSDs can be installed on DX CRAC units with some caution. Resistance to the use of variable-speed fans in data centers has mainly been driven by perceived fear that variable-speed operation of data center cooling may adversely affect its reliability. However, EPRI has tested VSDs on two of its data center CRAC units. It has found these units to be working satisfactorily without any problem down to 60% fan speeds while operating under adverse ambient conditions, under which it would have likely shown problems, if any. It may be quite practical to reduce fan speeds down to a safer zone of 70% (instead of 60% testing at EPRI) and still achieve 66% direct fan energy savings. Additional cooling energy savings would be derived from reduced fan heat from avoided fan power. Some manufactures do provide CRAC unit performance ratings on request and do not see red flags down to 60% speed. It is always good to check with your CRAC unit suppliers, but be aware that they may discourage it.

So how does one determine whether a particular data center is a good candidate for VSD installation and airflow management? There are several clues from CRAC and CRAH units' operational data. Follow the following simple procedures:

1. Start with gathering the following data. What is the ICT load? Generally, these data can be obtained from the UPS or power distribution unit (PDU) for the ICT load. If a UPS is located within the data center space, its heat losses are also to be included along with the ICT load. The ICT load can be measured in kW.

2. What is the CRAC units' total rated cooling capacity? Add cooling capacity and fan power of each of the CRAC units. The CRAC unit nominal capacity may be available in tons or Btu/hr of cooling. These numbers can be converted to equivalent kW cooling capacity. A ton of cooling can cool 3.52 kW of IT load. There is 3,412 Btu in each kWh, so the Btu/hr number needs to be divided by 3,412 to obtain its cooling capacity in kW.

3. Compare the ICT load (kW) against the total cooling capacity (kW). If ICT load is less than 80% of the CRAC unit cooling capacity, it is likely a good candidate - the lower the number, the more the savings opportunity.

4. Review the temperature of the CRAC unit return air. It is easily available from the CRAC unit display panel.

5. Review the temperature of the CRAC unit supply air. It may also be available from the CRAC unit display panel. If not, insert a temperature sensor near the supply air outlet. Be careful to get an average supply air temperature with DX CRAC units where compressors may be turning on and off.

6. Calculate temperature difference between return and supply air temperatures. If the temperature difference is less than 15°F, it is likely a good candidate - the lower the temperature difference number, the better the savings opportunity.

7. Review CRAC units' display panel operating data and look for cooling status. If it has chilled-water coils, it would provide the status of the chilled-water valve open position in percentage. Add and average data from all units.

8. If the CRAC units have compressors, its display panel will show how many compressors are running (such as 0%, 50%, or 100%, if it has two compressors). Add and average compressor run data from all units. Use caution in gathering data because compressors may cycle rapidly, sometime as soon as every three minutes. Add the compressors run status data and take an average.

9. If the average number for CRAH/CRAC cooling status is below 80% (in steps 7 or 8 above), it is likely a good candidate - the lower the number, the larger the savings potential.

10. Review CRAC units' historical performance data. Most CRAC units have historical data on fan run times as well as on run times of individual compressors. Take two readings over a period of time, say a week or so, and calculate run hours during this period. Calculate average compressor run time from the data. To calculate average run time for compressors, divide the sum of compressor run times with the number of compressors and fan run time. If it is a chilled-water unit, it may show average position of the chilled-water valve.

11. If the compressors' historical run time is less than 80%, or valve average open position is less than 80%, it is likely a good candidate.

12. Find out CRAC units' total airflow rates and fan power use. Add fan power of all units. Also add airflow of all units.

13. Divide total fan power by the ICT power. If the number is above 0.10 kW/kW, it is likely a good candidate and the larger the number, the more the savings opportunity.

14. Estimating fan power energy savings depends on many variables, but if we target fan energy use to be less than 0.06 kW/kW of ICT power, we can estimate annual savings by taking a difference between the current fan power use per unit of the ICT power and a target of 0.06 and multiply it by the number of hours in a year and the average electricity rates. This target of 0.06 kW/kW of ICT power has been selected based on the lower end of the LBNL airflow range of 0.07 to 0.50 kW/kW and some other data from the industry. The 0.06 kW/kW target should provide substantial energy savings without introducing unnecessary thermal risks within the data center.

15. Besides these quantitative numbers, we also need to review qualitatively whether good airflow management practices are being followed, such as hot and cold aisle arrangement, sealing cable cutout, blanking panels, spaces between racks, and empty rack spaces. Addressing these will help us reduce hot spots, but the energy savings will be derived from reducing airflow, either by shutting down some CRAC units or reducing airflow through the CRAC units.

Here are some quick examples of how energy savings were achieved in practice.

5.1 Case Study 1

This site is a small data center located within a large building with traditional hot and cold aisles and no containment. Six 30-ton CRAH units, each with a 7.5-HP fan, are located in the perimeter. A 300-kW UPS is located within the data center space with an operating load of 165 kW. Case Study 1 data center specifications:

- Nominal cooling capacity: 6*30*3.52 = 633 kW
- UPS output: 165 kW
- ICT load (including UPS eff.) : 165/0.88 = 188 kW
- ICT load/nominal cooling: 188/633 = 30%
- Rated fan power: 6*7.5*0.75 = 33.75 kW
- Rated fan power/ICT load: 33.75/165 = 0.205 kW/kW
- **Potential direct fan energy savings: (0.205-0.06)*165*8760 = 211,030 kWh/annually**

ICT load/cooling capacity (30%) is less than 80%, and it is a good candidate for VSD installation. A fan power of 0.205 kW/kW of the ICT power is larger than our target of 0.06 kW/kW of the ICT power, and also suggests it is a good candidate.

The VSDs were installed with the following results. The actual fan power was measured to be less than the rated fan motor power:

- Fan power before VSD installation: 30.6 kW/165 kW = 0.185 kW/kW
- After VSD installation: 6 kW/165 kW = 0.036 kW/kW
- Annual direct fan energy savings: (0.185-0.036)*165*8760 = 215,365 kWh
- Indirect cooling energy savings: 215,364/3.0 = 71,790 kWh
- **Total direct and indirect fan energy savings: 213,365 + 71,790 = 287,155 kWh/annually**

VSDs were installed along with several wireless temperature sensors in front of the ICT equipment racks that measured inlet air temperatures, which were processed by a control system that modulated the fan speeds of the CRAH units. The measured fan draw at full speed was about 90% of the rated fan power. More fan energy savings were realized than calculated because the measured fan power after VFD installation was only 0.036 kW/kW of the ICT power instead of the target of 0.06 kW/kW of the ICT power. The energy savings from the indirect cooling were calculated using cooling equipment coefficient of performance of 3.0. The payback period, without considering any incentives, was less than two years.

5.2 Case Study 2

The data is from the EPRI data center where VSDs on DX CRAC units are being demonstrated. The data center has a combined power distribution unit (PDU) load of 82 kW. The UPS is located outside of the raised-floor data center. The two 30-ton DX CRAC units have 10-HP motors and 15,000 rated cfm. Case Study 2 data center specifications:

- Nominal cooling capacity: 2*30*3.52 = 211 kW
- PDU load: 82 kW
- ICT load: 82 kW
- ICT load/nominal cooling: 82/211 = 39%
- Rated fan power: 2*10*0.75 = 15 kW
- Rated fan power/ICT load: 15/82 = 0.183 kW/kW
- **Potential direct fan energy savings: (0.183-0.06)*82*8760 = 88,353 kWh/annually**

ICT load/cooling capacity (39%) is below 80%, and it is a good candidate for VSD installation. Fan power of 0.183 kW/kW is larger than our target of 0.06 kW/kW, which also suggests it is a good candidate.

This site is a test site for demonstrating VSD installation on a DX CRAC unit. The VSDs were installed with the following results. The actual motor power draw was measured to be less than the rated power draw as calculated above:

- Fan power before VSD installation: 13.7 kW/82 kW = 0.167 kW/kW
- Fan power after VSD installation (70% fan speed): 4.6 kW/82 kW = 0.056 kW/kW
- Fan power after VSD installation (60% fan speed): 3.1 kW/ 82 kW = 0.038 kW/kW
- Annual direct fan energy savings (70% fan): (0.167-0.056)*82*8760 = 79,734 kWh
- Indirect cooling energy savings (70% fan): 79,734/3.0 = 26,578 kWh
- **Total direct and indirect fan energy savings: 79,734 + 26,578 = 106,312 kWh/annually**

VSDs were installed, and their speed was put in manual control. The measured fan draw at full speed was about 90% of the rated fan power. Less fan energy savings were realized than calculated because the measured fan power at full speed was less than the rated numbers used in calculations. The fan power after VSD installation was close to the target at 0.056 kW/kW at 70% fan speed. The energy savings from indirect cooling were calculated using cooling equipment coefficient of performance of 3.0.

The system ran successfully for nearly 18 months. The above results are from installation of VSDs and no other changes to the data center floor, such as air containment, blanking panels, and stopping air leakage from tile cutouts. The data center and the DX CRAC units have been working without any problem for the last 18 months. One observation that visitors to this data center often make is "how quiet it is." Wireless sensors for monitoring temperature distribution within the data center space and using those temperature sensors to modulate fan speed have already been implemented.

The above case studies clearly show that significant energy savings in data centers are possible with reductions in fan power and airflow management, and they also show a simple method for estimating energy savings.

GLOSSARY

Term	Definition
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTU	British Thermal Unit
CFM	Cubic Feet Per Minute
CRAC	Computer Room Air Conditioner
CRAH	Computer Room Air Handler
DX	Direct Expansion
EER	Energy Efficiency Ratio
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
HP	Horsepower
HVAC	Heating Ventilation and Air Conditioning
ICT	Information and Communication Technology
kW	Kilo-Watt
kWh	Kilo-Watt-hour
LBNL	Lawrence Berkeley National Laboratory
MW	Mega Watt
PDU	Power Distribution Unit
PUE	Power Usage Efficiency
SEER	Seasonal Energy Efficiency Ratio
UPS	Uninterruptible Power Supply
VFD	Variable Frequency Drive
VSD	Variable Speed Drive

APPENDIX A:
Test Data

The test data supporting the charts and figures used in this report are presented here. Also presented are the manufacturers' performance data.

Table 2: IT and Cooling Energy Use versus Indoor Fan Speed Data from EPRI Site

CRAC Units Operational Status	IT Equipment Average Energy Use from UPS, kWh/Hr	Total DX CRAC Units (Indoor and Outdoor) Average Energy Use, kWh/Hr	Total Cooling Energy Use Reduction Compared to 100% Fan Speed, kWh/Hr	Total Fan Energy Reduction Compared to 100% Fan Speed, kWh/Hr	Total Compressor Energy Reduction Compared to 100% Fan Speed, kWh/Hr	Total Cooling Energy Use Reduction Compared to 100% Fan Speed, kWh/kWh of the IT Energy Use	Total Fan Energy Use Reduction Compared to 100% Fan Speed, kWh/kWh of the IT Energy Use	Total Compressors Energy Use Reduction Compared to 100% Fan Speed, kWh/kWh of the IT Energy Use
100% Fan Speed, Manual Setting	84.12	53.84	0	0	0	0	0	0
90% Fan Speed, Manual Setting	88.03	46.16	-7.68	-3.7	-3.98	-8.7%	-4.2%	-4.5%
80% Fan Speed, Manual Setting	84.46	43.38	-10.46	-6.80	-3.66	-12.4%	-8.1%	-4.3%
80% Fan Speed, Manual Setting	84.32	43.59	-10.26	-6.80	-3.46	-12.2%	-8.1%	-4.1%
Vigilent Control of Fan Speed, Minimum Setting 70%	84.01	39.52	-14.32	-9.10	-5.22	-17.0%	-10.8%	-6.2%
Vigilent Control of Fan Speed, Minimum Setting 70%	85.55	39.69	-14.15	-9.10	-5.05	-16.5%	-10.6%	-5.9%
Vigilent Control of Fan Speed, Minimum Setting 60%	85.57	37.21	-16.63	-10.60	-6.03	-19.4%	-12.4%	-7.0%

Table 3: Energy Performance Data Before and After Fan Speed Change from 100% to 80%

CRAC Units operational status	IT Equipment Avg Energy Use from UPS, kWh/Hr	CRAC A Indoor Unit, Avg Energy Use, kWh/Hr	CRAC A Outdoor unit, Avg Energy Use, kWh/Hr	CRAC B Indoor Unit, Avg Energy Use, kWh/Hr	CRAC B Outdoor Unit, Avg Energy Use, kWh/Hr	Total CRAC Indoor and Outdoor Units Avg Energy Use, kWh/Hr	Total Indoor CRACs Avg Fan Energy Use, kWh/Hr	Total Indoor CRACs Avg Compressor Energy Use, kWh/Hr	Cooling Support Power, kWh/kWh of the IT Equipment	Partial Cooling Only PUE
100% Fan Speed, Manual Setting	84.12	24.84	1.85	25.57	1.58	53.84	13.70	40.14	0.64	1.64
80% Fan Speed, Manual Setting	84.46	18.43	1.83	21.40	1.72	43.38	6.90	36.48	0.51	1.51
Change in Energy Use, kWh/Hr	0.33	-6.42	-0.01	-4.17	0.14	-10.46	-6.80	-3.66	-0.13	-0.13
% Change in Energy Use	**0.4%**	-25.8%	-0.6%	-16.3%	9.0%	**-19.4%**	**-49.6%**	**-9.1%**	**-19.7%**	-7.7%

(Table 3 Note: Under manual operations)

Table 4: Energy Performance Data Before and After Fan Speed Change

CRAC Units Operational Status	IT Equipment Avg Energy Use from UPS, kWh/Hr	CRAC A Indoor Unit, Avg Energy Use, kWh/Hr	CRAC A Outdoor Unit, Avg Energy Use, kWh/Hr	CRAC B Indoor Unit, Avg Energy Use, kWh/Hr	CRAC B Outdoor Unit, Avg Energy Use, kWh/Hr	Total CRAC Indoor and Outdoor Units Avg Energy Use, kWh/Hr	Total Indoor CRACs Avg Fan Energy Use, kWh/Hr	Total Indoor CRACs Avg Compressor Energy Use, kWh/Hr	Cooling Support Power, kWh/kWh of the IT Equipment	Partial Cooling Only PUE
80% Fan Speed, Manual Setting	84.32	18.74	1.67	21.55	1.62	43.59	6.90	36.69	0.52	1.52
Vigilent Control of Fan Speed, Minimum Setting 70%	84.01	15.80	1.64	20.41	1.67	39.52	4.60	34.92	0.47	1.47
Change in Energy Use, kWh/Hr	-0.30	-2.94	-0.03	-1.14	0.04	-4.06	-2.30	-1.76	-0.05	-0.05
% Change in Energy Use	**-0.4%**	-15.7%	-1.7%	-5.3%	2.5%	**-9.3%**	**-33.3%**	**-4.8%**	**-9.0%**	-3.1%

(Table 4 data from 80% under Manual Setting to Vigilent Control with 70% Minimum Speed Setting)

Table 5: Energy Performance Data Before and After Fan Speed Change

CRAC Units Operational Status	IT Equipment Avg Energy Use from UPS, kWh/Hr	CRAC A Indoor Unit, Avg Energy Use, kWh/Hr	CRAC A Outdoor Unit, Avg Energy Use, kWh/Hr	CRAC B Indoor Unit, Avg Energy Use, kWh/Hr	CRAC B Outdoor Unit, Avg Energy Use, kWh/Hr	Total CRAC Indoor and Outdoor Units Avg Energy Use, kWh/Hr	Total Indoor CRACs Avg Fan Energy Use, kWh/Hr	Total Indoor CRACs Avg Compressor Energy Use, kWh/Hr	Cooling Support Power, kWh/kWh of the IT Equipment	Partial Cooling Only PUE
Vigilent Control of Fan Speed, Minimum Setting 70%	85.55	15.97	2.63	18.81	2.27	39.69	4.60	35.09	0.46	1.46
Vigilent Control of Fan Speed, Minimum Setting 60%	85.57	15.09	2.86	16.89	2.38	37.21	3.10	34.11	0.43	1.43
Change in Energy Use, kWh/Hr	0.02	-0.88	0.23	-1.93	0.10	-2.47	-1.50	-0.97	-0.03	-0.03
% Change in Energy Use	**0.0%**	-5.5%	8.6%	-10.2%	4.6%	**-6.2%**	**-32.6%**	**-2.8%**	**-6.3%**	-2.0%

(Table 5 Note: Data is under Vigilent Control, going from 70% to 60% Minimum Speed Setting)

Table 6: Fans and Compressors Run Time Fraction at the EPRI site

Date	Fan Speed	Fan power Kw	Temp set point, F	Relative Humidity readings, %	fan speed	Fan power	Fan kWh	Fan Accumulated Run hours	Compressor 1 Accumulated Run Hours	Compressor 2 Accumulated Run Hours	CRAC Fan Run hours between subsequent readings	Compressor 1 Run Hours between subsequent readings	Compressor 2 Run Hours between subsequent readings	Total compressors run hours	Compressors run fractions
4/1/2010	100%		68	39				36523	15025	14947					
1/28/2011	100%							43892	18334	18533	7369	3309	3586	6895	47%
6/8/2011	100%		67	51				47079	19918	20138	3187	1584	1605	3189	50%
6/14/2011	100%							47233	19995	20214	154	77	76	153	50%
7/21/2011	100%				100%	6.6	296								
8/5/2011	100%		69	47	100%	6.6	2909	48473	20598	20812	1240	603	598	1201	48%
8/8/2011	100%	6.6			100%	6.6		48561	20640	20849	88	42	37	79	45%
8/12/2011	100%	6.6			100%	6.6	4336	48664	20685	20899	103	45	50	95	46%
8/12/2011	90%	4.8			90%	4.8	4336	48664	20685	20899					
8/22/2011	90%	4.8			90%	4.8	5688	48907	20796	21009	243	111	110	221	45%
8/22/2011	80%	3.3			80%	3.3	5688	48907	20796	21009					
8/23/2011	80%	3.3	69	50	80%	3.3	5748	48928	20805	21018	21	9	9	18	43%
8/26/2011	80%	3.3	69	50	80%	3.3	6042	49005	20837	21054	77	32	36	68	44%
9/9/2011	80%	3.3	69	50	80%	3.3	7354	49349	20989	21205	344	152	151	303	44%
9/12/2001					70%										
9/21/2011	70%	2.2	*69*	50	70%	2.2	8189	49638	21116	21337	*289*	*127*	*132*	*259*	*45%*
9/23/2011	70%	2.2	69	50	70%	2.3	8315	49687	21139	21357	49	23	20	43	44%
10/4/2011	70%	2.2	69	50	60%	1.5	9014	49959	21261	21479	272	122	122	244	45%
10/4/2011	60%	1.5	69	50	60%	1.5	9014	49959	21261	21479					
10/14/2011	60%	1.5	69	50	60%	1.5	9444	50204	21368	21586	245	107	107	214	44%
10/21/2011	60%	1.5	69	50	60%	1.5	9746	50374	21441	21662	170	73	76	149	44%
10/31/2011	60%	1.5	69	50	60%	1.5	10165	50612	21553	21772	238	112	110	222	47%
11/4/2001	60%	1.5	69	50	60%	1.5	10350	50716	21600	21817	104	47	45	92	44%
11/11/2011	60%	1.5	69	50	60%	1.5	10652	50886	21675	21898	170	75	81	156	46%
11/23/2011	0.6	1.5	69	50	60%	1.5	11165	51177	21823	22031	291	148	133	281	48%
12/2/2011	60%	1.5	*69*	50	60%	1.5	11563	51400	21931	22154	*223*	*108*	*123*	*231*	*52%*
12/14/2011	60%	1.5	69	50	60%	1.5	12083	51693	22100	22310	293	169	156	325	55%

Table 7: Fans and Compressors Run Time Fraction at the EPRI site (continued)

Date	Fan Speed	Fan power kW	Temp set point, F	Relative Humidity readings, %	fan speed	Fan power	Fan kWh	Fan Accumulated Run hours	Compressor 1 Accumulated Run Hours	Compressor 2 Accumulated Run Hours	CRAC Fan Run hours between subsequent readings	Compressor 1 Run Hours between subsequent readings	Compressor 2 Run Hours between subsequent readings	Total compressors run hours	Compressors run fractions
4/1/2010	100%		70	36				36661	18906	19044					
1/28/2011	100%							44026	23646	23797	7365	4740	4753	9493	64%
6/8/2011	100%		69	49				47211	25703	25856	3185	2057	2059	4116	65%
6/14/2011	100%							47363	25798	25946	152	95	90	185	61%
7/21/2011	100%				100%	7.0	151	48255	26346	26493	892	548	547	1095	61%
8/5/2011	100%		69	47	100%	7.0	2998	48608	26574	26723	353	228	230	458	65%
8/8/2011	100%	7.1			100%	7.1		48696	26628	26770	88	54	47	101	57%
8/12/2011	100%	7.1			100%	7.1	4530	48798	26691	26840	102	63	70	133	65%
8/12/2011	90%	5.2			90%	5.2	4530	48798	26691	26840					
8/22/2011	90%	5.2			90%	5.2	5961	49042	26832	26980	244	141	140	281	58%
8/22/2011	80%	3.6			80%	3.6	5961	49042	26832	26980					
8/23/2011	80%	3.6	68	50	80%	3.6	6046	49062	26845	26992	20	13	12	25	63%
8/26/2011	80%	3.6	68	50	0.8	3.6	6360	49139	26888	27036	77	43	44	87	56%
9/9/2011	80%	3.6	68	50	0.8	3.6	7757	49483	27083	27234	344	195	198	393	57%
9/12/2001					0.7										
9/21/2011	70%	2.4	*68*	50	0.7	2.4	8635	49772	27247	27397	*289*	*164*	*163*	*327*	*57%*
9/23/2011	70%	2.4	68	50	0.7	2.4	8767	49821	27272	27422	49	25	25	50	51%
10/4/2011	70%	2.4	68	50	0.6	1.6	9501	50092	27417	27566	271	145	144	289	53%
10/4/2011	60%	1.6	68	50	0.6	1.6	9501	50092	27417	27566					
10/14/2011	60%	1.6	68	50	0.6	1.6	9944	50337	27547	27699	245	130	133	263	54%
10/21/2011	60%	1.6	68	50	0.6	1.6	10253	50508	27638	27788	171	91	89	180	53%
10/31/2011	60%	1.6	68	50	0.6	1.6	10683	50745	27764	27911	237	126	123	249	53%
11/4/2001	60%	1.6	68	50	0.6	1.6	10871	50850	27824	27970	105	60	59	119	57%
11/11/2011	60%	1.6	68	50	0.6	1.6	11180	51020	27915	28074	170	91	104	195	57%
11/23/2011	0.6	1.6	68	50	0.6	1.6	11707	51310	28072	28223	290	157	149	306	53%
12/2/2011	60%	1.6	*68*	50	0.6	1.6	12112	51533	28185	28335	*223*	*113*	*112*	*225*	*50%*
12/14/2011	60%	1.6	69	50	0.6	1.6	12644	51826	28336	28490	293	151	155	306	52%

Table 8: Manufacturer's Performance Data for DX CRAC Units at EPRI

DH380A-AA00 Performance

Both Compressors Running (100% Capacity)

Sensibile Capacity kBTU
Latent Capacity kBTU
Evapator Temp °F

<40F evap temp coil is subject to freezing!!

VFD Speed

Ambient	Return Conditions	100% Sens	100% Lat	100% Evap T	100% PWR per Comp KW	100% Fan kW	90% Sens	90% Lat	90% Evap T	90% PWR per Comp KW	90% Fan kW	80% Sens	80% Lat	80% Evap T	80% PWR per Comp KW	80% Fan kW	70% Sens	70% Lat	70% Evap T	70% PWR per Comp KW	70% Fan kW	66.7% Sens	66.7% Lat	66.7% Evap T	66.7% PWR per Comp KW	66.7% Fan kW	Cond Fan kW
95F	80DB/67WB	301.33	65	47.8	16.728	10.17	288.28	76.2	47	16.62	7.42	273.33	86.4	46.2	16.497	5.47	257.3	96.6	45	16.341	3.9	251.74	99.7	44.6	16.281	3.46	2.23
	75DB/62WB	299.83	37.5	43.4	16.126	10.17	286.78	47.8	42.7	16.024	7.42	272.33	59.1	41.8	15.899	5.47	256.8	69.6	40.6	15.745	3.9	251.14	72.7	40.2	15.686	3.46	2.23
	72DB/60WB	285.33	40.9	41.7	15.889	10.17	273.88	51	40.9	15.787	7.42	260.63	60.5	40	15.668	5.47	245.6	68.8	39	15.513	3.9	240.94	72.1	38.5	15.448	3.46	2.23
	72DB/58.6WB	326.83	0	41.7	15.9	10.17	291.58	24.8	39.7	15.616	7.42	276.83	36.1	38.8	15.492	5.47	260.6	47.1	37.7	15.337	3.9	254.94	50.6	37.3	15.278	3.46	2.23

Ambient	Return Conditions	100% Sens	100% Lat	100% Evap T	100% PWR per Comp KW	100% Fan PWR	90% Sens	90% Lat	90% Evap T	90% PWR per Comp KW	90% Fan PWR	80% Sens	80% Lat	80% Evap T	80% PWR per Comp KW	80% Fan PWR	70% Sens	70% Lat	70% Evap T	70% PWR per Comp KW	70% Fan PWR	66.7% Sens	66.7% Lat	66.7% Evap T	66.7% PWR per Comp KW	66.7% Fan PWR	Cond Fan kW
80F	80DB/67WB	312.13	83.6	46.3	14.52	10.17	296.78	93.9	45.5	14.44	7.42	283.93	103.7	44.5	14.34	5.47	267.8	112.8	43.3	14.22	3.9	262.14	115.6	42.9	14.175	3.46	2.23
	75DB/62WB	310.83	53	41.9	14.082	10.17	297.98	64.5	41.1	14.005	7.42	283.13	74	40.1	13.903	5.47	266.9	82.9	39	13.777	3.9	261.64	86.3	38.5	13.7333	3.46	2.23
	72DB/60WB	296.53	56.2	40.2	13.903	10.17	284.38	65.1	39.4	13.821	7.42	271.23	74.2	38.4	13.715	5.47	256.6	82.4	37.2	13.595	3.9	251.44	85	36.8	13.549	3.46	2.23
	72DB/58.6WB	316.23	27.9	38.9	13.779	10.17	302.68	39	38.1	13.688	7.42	293.43	46	37.5	13.625	5.47	271.2	59.7	36	13.463	3.9	265.44	62.9	35.5	13.419	3.46	2.23

Ambient	Return Conditions	100% Sens	100% Lat	100% Evap T	100% PWR per Comp KW	100% Fan PWR	90% Sens	90% Lat	90% Evap T	90% PWR per Comp KW	90% Fan PWR	80% Sens	80% Lat	80% Evap T	80% PWR per Comp KW	80% Fan PWR	70% Sens	70% Lat	70% Evap T	70% PWR per Comp KW	70% Fan PWR	66.7% Sens	66.7% Lat	66.7% Evap T	66.7% PWR per Comp KW	66.7% Fan PWR	Cond Fan kW
65F	80DB/67WB	315.63	89.7	45.8	13.77	10.17	302.18	99.7	45	13.71	7.42	287.33	109.1	44	13.62	5.47	271.2	117.9	42.8	13.522	3.9	265.54	120.7	42.3	13.469	3.46	1.67
	75DB/62WB	313.03	56.8	41.6	13.672	10.17	299.98	67.3	40.8	13.609	7.42	285.13	76.7	39.8	13.505	5.47	269.3	86	38.6	13.384	3.9	263.64	88.9	38.2	13.339	3.46	1.67
	72DB/60WB	297.83	57.8	40	13.631	10.17	285.68	66.8	39.2	13.565	7.42	272.63	75.9	38.2	13.468	5.47	258	83.9	37	13.353	3.9	252.84	86.6	36.5	13.298	3.46	1.67
	72DB/58.6WB	317.63	29.8	38.7	13.52	10.17	304.08	40.7	37.9	13.443	7.42	288.93	51.2	37	13.349	5.47	272.6	61.2	35.8	13.219	3.9	266.84	64.4	35.3	13.172	3.46	1.67

One Compressor Running (50% Capacity)

VFD Speed

Ambient	Return Conditions	100% Sens	100% Lat	100% Evap T	100% PWR per Comp KW	100% Fan kW	90% Sens	90% Lat	90% Evap T	90% PWR per Comp KW	90% Fan kW	80% Sens	80% Lat	80% Evap T	80% PWR per Comp KW	80% Fan kW	70% Sens	70% Lat	70% Evap T	70% PWR per Comp KW	70% Fan kW	66.7% Sens	66.7% Lat	66.7% Evap T	66.7% PWR per Comp KW	66.7% Fan kW	Cond Fan kW
95F	80DB/67WB	180.798	0	57.6	15.182	10.17	172.968	0	56.5	15.131	7.42	163.998	0	55.3	15.066	5.47	154.38	15.9	52.8	14.937	3.9	151.044	20.5	52.6	14.92	3.46	2.23
	75DB/62WB	179.898	0	54	14.966	10.17	172.068	0	53	14.943	7.42	163.398	0	51.8	14.876	5.47	154.08	0	50.4	14.786	3.9	150.684	11.7	48.7	14.689	3.46	2.23
	72DB/60WB	171.198	0	51.8	14.875	10.17	164.328	0	50.8	14.796	7.42	156.378	0	49.7	14.774	5.47	147.36	0	48.3	14.665	3.9	144.564	0	47.7	14.63	3.46	2.23
	72DB/58.6WB	196.098	0	51.8	14.875	10.17	174.948	0	50.8	14.821	7.42	166.098	0	49.7	14.75	5.47	156.36	0	48.3	14.665	3.9	152.964	0	47.7	14.631	3.46	2.23

Ambient	Return Conditions	100% Sens	100% Lat	100% Evap T	100% PWR per Comp KW	100% Fan PWR	90% Sens	90% Lat	90% Evap T	90% PWR per Comp KW	90% Fan PWR	80% Sens	80% Lat	80% Evap T	80% PWR per Comp KW	80% Fan PWR	70% Sens	70% Lat	70% Evap T	70% PWR per Comp KW	70% Fan PWR	66.7% Sens	66.7% Lat	66.7% Evap T	66.7% PWR per Comp KW	66.7% Fan PWR	Cond Fan kW
80F	80DB/67WB	187.278	0	56.8	13.863	10.17	179.268	0	55.7	13.837	7.42	170.358	0	54.5	13.802	5.47	160.68	21.5	52.3	13.744	3.9	157.284	26	52	13.737	3.46	2.23
	75DB/62WB	186.498	0	53.2	13.751	10.17	178.788	0	52.2	13.742	7.42	169.878	0	51	13.695	5.47	160.14	12.5	48.5	13.599	3.9	156.984	16.8	56.2	13.589	3.46	2.23
	72DB/60WB	177.918	0	51.2	13.855	10.17	170.628	0	50.3	13.807	7.42	162.738	0	49.1	13.783	5.47	153.96	0	47.6	13.713	3.9	150.864	11.5	46	13.64	3.46	2.23
	72DB/58.6WB	189.738	0	51.2	13.855	10.17	181.608	0	50.3	13.807	7.42	176.058	0	49.1	13.783	5.47	162.72	0	47.6	13.713	3.9	159.264	0	47	13.689	3.46	2.23

Ambient	Return Conditions	100% Sens	100% Lat	100% Evap T	100% PWR per Comp KW	100% Fan PWR	90% Sens	90% Lat	90% Evap T	90% PWR per Comp KW	90% Fan PWR	80% Sens	80% Lat	80% Evap T	80% PWR per Comp KW	80% Fan PWR	70% Sens	70% Lat	70% Evap T	70% PWR per Comp KW	70% Fan PWR	66.7% Sens	66.7% Lat	66.7% Evap T	66.7% PWR per Comp KW	66.7% Fan PWR	Cond Fan kW
65F	80DB/67WB	187.278	0	56.8	13.863	10.17	179.268	0	55.7	13.837	7.42	170.358	0	54.5	13.802	5.47	160.68	21.5	52.3	13.744	3.9	157.284	26	52	13.737	3.46	1.67
	75DB/62WB	186.498	0	53.2	13.751	10.17	178.788	0	52.2	13.742	7.42	169.878	0	51	13.695	5.47	160.14	12.5	48.5	13.599	3.9	156.984	16.8	56.2	13.589	3.46	1.67
	72DB/60WB	177.918	0	51.2	13.855	10.17	170.628	0	50.3	13.807	7.42	162.738	0	49.1	13.783	5.47	153.96	0	47.6	13.713	3.9	150.864	11.5	46	13.64	3.46	1.67
	72DB/58.6WB	189.738	0	51.2	13.855	10.17	181.608	0	50.3	13.807	7.42	176.058	0	49.1	13.783	5.47	162.72	0	47.6	13.713	3.9	159.264	0	47	13.689	3.46	1.67

(Table 7 Note: Data at Different Fan Speeds, data values in red color shows unit operation out of the recommended range)

Table 9: Manufacturer's Data for Water Cooled DX CRAC Unit at NetApp

Performance of Water Cooled unit
Unit Model # CAW-2034

% Of CFM	E.W.T. Condenser	Return Air Temperature	Total Cooling Capacity	Sensible Cooling Capacity	Power per Compressor	Fan kw
100%	80	80/67	302	279	7690	5.371
		75/62.5	292	238		
		72/60	236	214		
		72/58.6	247	243		
90%	80	80/67	300	257	7680	4.401
		75/62.5	271	218		
		72/60	218	196		
		72/58.6	227	224		
80%	80	80/67	299	234	7670	3.581
		75/62.5	249	198		
		72/60	200	178		
		72/58.6	202	200		
70%	80	80/67	288	209	7650	2.909
		75/62.5	224	177		
		72/60	181	159		
		72/58.6	177	175		
66.67%	80	80/67	281	201	7640	2.611
		75/62.5	216	170		
		72/60	174	152		
		72/58.6	169	167		
100%	75	80/67	309	281	7290	5.371
		75/62.5	299	241		
		72/60	240	218		
		72/58.6	252	248		
90%	75	80/67	306	258	7280	4.401
		75/62.5	278	220		
		72/60	221	194		
		72/58.6	228	225		
80%	75	80/67	299	238	7270	3.581
		75/62.5	252	199		
		72/60	206	184		
		72/58.6	207	204		
70%	75	80/67	291	211	7255	2.909
		75/62.5	225	178		
		72/60	182	162		
		72/58.6	180	176		
66.67%	75	80/67	288	211	7240	2.611
		75/62.5	228	176		
		72/60	185	154		
		72/58.6	177	168		

(Table 8 Note: Data at Different Fan Speeds, data values in red color shows unit operation out of the recommended range)

Table 9: continued

% Of CFM	E.W.T. Condenser	Return Air Temperature	Total Cooling Capacity	Sensible Cooling Capacity	Power per Compressor	Fan kw
100%	70	80/67	318	288	6910	5.371
		75/62.5	304	251		
		72/60	260	224		
		72/58.6	254	248		
90%	70	80/67	310	280	6900	4.401
		75/62.5	291	245		
		72/60	242	198		
		72/58.6	230	226		
80%	70	80/67	302	268	6890	3.581
		75/62.5	265	210		
		72/60	248	185		
		72/58.6	218	201		
70%	70	80/67	296	212	6875	2.909
		75/62.5	227	181		
		72/60	186	166		
		72/58.6	181	179		
66.67%	70	80/67	294	211	6860	2.611
		75/62.5	224	172		
		72/60	194	165		
		72/58.6	180	174		

Table 10: Compressor Run Times at Various Fan Speeds

Fan Speed	Subsequent period between readings (avg of fan run hours)	All four compressors run hours	% time compressors run	Average % time compressors on	Average IT load, kW	Average % time compressors onper kW
	3186	7305	57.3%			
	153	338	55.2%			
	446	1095	61.4%			
	796.5	1659	52.1%			
	88	180	51.1%			
100%	102.5	228	55.6%	56.6%	82.2	0.689%
90%	243.5	502	51.5%	51.5%	81.1	0.636%
	20.5	43	52.4%			
	77	155	50.3%			
80%	344	696	50.6%	50.6%	81.3	0.623%
	289	586	50.7%			
	49	93	47.4%			
70%	271.5	533	49.1%	49.7%	80.2	0.620%
	245	477	48.7%			
	170.5	329	48.2%			
	237.5	471	49.6%			
	104.5	211	50.5%			
	170	351	51.6%			
	290.5	587	50.5%			
	223	456	51.1%			
60%	293	631	53.8%	50.6%	79	0.640%