Pacific Gas and Electric Company

Emerging Technologies Program

Application Assessment Report #0912

Data Center
Air Management Research

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SUMMARY

Data centers are among the most energy-intensive facilities. Air management is not only imperative for energy management but also for thermal management. The goal of air management is to supply as little supply air as possible at as high temperature as possible without adversely affecting the thermal IT-equipment environment. Several common air management measures were included in the Computational Fluid Dynamics (CFD) modeling to explore the energy-saving potentials. Measured data were also included in an effort to verify the modeling. The results will help improve the prediction of energy savings as well as improve the DOE Air Management (AM) Software Tool.

Key project findings include the following:

- A number of case studies indicate fan energy savings in the 70-90% range and chiller energy savings in the 15-25% range (~35% HVAC energy savings) with effective air management.
- For good air management, the modeled airflows and the airflows calculated by the AM Tool show similar trends although the supply airflow is higher for the modeled data. For poor air management, the data sets diverge but the results cannot be generalized based on this study alone.
- The PG&E calculated potential minimum over-ventilation of the data center is a perfect match with the CFD modeling and the AM Tool. The fact that the same supply airflow was deduced from three methods provides evidence that achieving much less than 20% over-ventilation is difficult.
- The PG&E measured initial over-ventilation is consistent with the CFD modeling and the AM Tool when considering that it represents CAV fans and CRAC return temperature sensing whereas the modeling and the Tool assume ideal operation with VAV fans and IT-equipment intake temperature sensing.
- Maximizing blanking panels in the IT-equipment racks and minimizing floor leakage, especially with full cold-aisle containment provide the highest HVAC energy savings, especially with air-side economizers.
- Certain combinations of poor air management may prove more benign than generally thought. Since it is difficult to know exactly what those combinations are, well-organized hot and cold air separation is still the best approach.
- The modeling shows no change in over-ventilation with CAV fans compared to VAV fans. This implies that the airflow distribution was comparable. But, CAV fans cannot guarantee a match between CRAC and IT-equipment airflow.
- At higher IT-equipment heat densities the relative floor leakage is reduced since the number of perforated tiles is increased. By simply elevating the heat density (with all other variables unchanged) the air management effectiveness improves.
- Whatever thermal standard adopted, the effect of air-management measures on the IT-equipment environment should be checked. The Rack Cooling Index (RCI) was used for this purpose. PG&E did not use such a yardstick.
- This report points to areas where more work may be needed, including refinements to the PG&E Air Management Incentive Program and the AM Tool.

1. PROJECT BACKGROUND

Data centers are among the most energy intensive facilities in the commercial sector, requiring immense amounts of energy to both run and cool powerful computers. These facilities consume up to fifty times the electric energy of standard office spaces. With such large power consumption, they are targets for energy-efficiency measures that can save money and energy.

Due to the critical nature of the vast majority of data centers, energy-efficiency measures must not reduce the IT-equipment reliability. The goal of air management is to supply as little cooling air as possible at as high temperature as possible without adversely affecting the thermal equipment environment. One significant difference compared to other energy-saving measures is that air management often impacts the environment. Thus, it needs to balance the thermal conditions with energy savings to avoid sub-optimizations.

Air management for data centers includes the design details that go into minimizing mixing between the cool air supplied to the IT-equipment racks and the hot air exhausted from the racks. More specifically, the objective is to minimize recirculation of hot air and minimize by-pass of cold air. Much of the cold air supplied to keep the equipment operating is often wasted because it is misdirected and mixes with the hot exhaust air. With more efficient airflow, supply fans can be turned down or off and supply temperatures can be turned up, both saving energy.

Correctly designed, air management can reduce operating costs, reduce CO_2 emissions, reduce capital investments, improve equipment reliability and longevity, and regain cooling capacity. The operating cost reductions can be very large. Energy costs for chiller systems and fan systems can be reduced by 20% and 80%, respectively. Regaining capacity may allow companies to delay or avoid costly facility upgrades or relocations.

Energy Assessment Tools for data centers are currently being developed by the Department of Energy (DOE) under the Save Energy Now program for evaluating major facility systems. This assessment suite of software tools (DC Pro) will be freely available for use by anyone interested in identifying energy savings for data centers, and includes an Air Management (AM) Tool (DOE 2010).

During the development of the AM Tool, difficulties in estimating the energy savings (and economic impact) with various measures were highlighted. It was concluded that the AM Tool's internal data ("lookup tables") needs to be enhanced. The present project is part of that effort. With the planned enhancements, the AM Tool may be part of a foundation for developing reliable air-management guidelines and for supporting utility incentive programs.

2. PROJECT OBJECTIVES

Savings from air-management is achieved by increasing the supply air temperature and/or turning down or off supply fans. A number of air management measures can be introduced in data centers to accomplish this goal. By applying a more rigorous methodology, this research focuses on how air management can be improved to save energy without negatively affecting the thermal IT-equipment environment and, in turn, the IT-equipment reliability. The results will also help improve the quality of the DOE Air Management (AM) Software Tool's internal (lookup) data.

A combination of Computational Fluid Dynamics (CFD) modeling of a representative data center and physical verification will provide improved data. With CFD modeling a large number of systematic parametric runs, where each input parameter is changed at a time, can be performed in a relatively short time. PG&E's existing measured data sets from data centers will be utilized for the verification of the computer models.

The first step in the methodology includes modeling of select cases with real-world data center deficiencies in order to test different air-management measures and determine the supply airflow rate required to maintain a specified level of thermal IT-equipment intake conditions as measured by the Rack Cooling Index (RCI)™. Selecting the parameters includes some hard choices.

The eight measures considered key to air management in the DOE AM Tool will be used as a starting point in this study:

- Build aisle containment to reduce mixing of cold and hot air
- Install blanking panels in and in between racks to reduce hot recirculation
- Seal leakages in the raised floor to reduce by-pass air
- Place perforated tiles in cold equipment aisles only to reduce by-pass air
- Use optimal EC-Class (rack ventilation path) to reduce recirculation air
- Enhance controls including sensing location and airflow adjustments
- Ensure adequate air handler modularity and proximity to the IT-equipment
- Implement cable and pipe management in the raised-floor plenum.

Some measures may not save energy per se, but provide more effective cooling of the IT-equipment and allow more load to be handled by existing cooling equipment. Other solutions such as aisle containment provide great potentials for energy savings. A "killer" measure is one that has high applicability and provides high energy savings. An example is to place perforated floor tiles in cold aisles only. It is easy and inexpensive to implement (high applicability) and the energy savings can be great depending on the original tile layout.

Specifically, the project objective is to improve on the understanding of the energy impact of the eight individual air-management measures, each assigned three quality levels. In addition, the objective is to determine whether the groupings of the eight measures into three aggregate measures are adequate. The physically related individual measures were initially introduced to make the design of the DOE AM Tool lookup tables more manageable and the fact that there was not enough granular data. The objective with the physical verification is to verify that the model results correspond to actual measured data.

A parametric study based on CFD modeling and physical verification can be both costly and time consuming. Due to the limited scope of the present project, it should be considered an exploratory effort rather than an optimization study. As such, it will highlight further research needs.

3. AIR MANAGEMENT DATA REVIEW REPORT

Introduction

The purpose of this Air Management Data Review Report is to review, analyze, and summarize some of the available data and research on air management, including the following:

- Review existing data center air management data from PG&E's programs and other industry sources

- Analyze and summarize the air management data to show:
  - Air management characteristics of data centers
  - Types of air management measures available
  - Range of energy savings achieved or estimated.

- Perform an internet search to identify similar research characterizing the energy savings possible from air management measures to better align current efforts.

The Air Management Data Review Report first reviews data on thermal management in data centers. There needs to be a thermal check when introducing air management measures to save energy in data center. Since thermal performance metrics play a key role in understanding the thermal conditions, relevant metrics are discussed followed by reviewing data from a couple of sources. The Report continues with reviewing and analyzing data on energy management in a similar fashion to the thermal management section. Finally, the air management data are summarized in a table with energy savings from a number of case studies.

3.1 Thermal Management

Although thermal and energy management are intertwined, the focus is generally on one or the other. For the purpose of air management, however, they need to be considered in tandem. Thermal metrics play a key role in characterizing the thermal environment.

3.1.1 Engineered Air Management Thermal Metrics

This section reviews thermal performance metrics for air management in data centers, including their purpose, definition, and interpretation. The first metric (RCI) will be discussed in more detail compared to the other metrics since it will be used as the thermal yardstick. This metric will help ensure that air management measures will not degrade the thermal IT-equipment environment.

Rack Cooling Index (RCI)™ (Herrlin 2005) is a measure of conformance or compliance with IT-equipment inlet temperature specifications. The RCI is one of two high-level air management metrics incorporated into the DOE Air-Management Tool (DOE 2010).

Purpose
The RCI is a dimensionless measure of how effectively the IT-equipment is cooled and maintained within a given intake temperature specification. Out-of-bound temperatures may affect equipment reliability and longevity. Compared to analyzing individual intake temperatures, the RCI allows a large amount of measured or CFD generated temperature data to be condensed and presented in a standardized way. The metric can be used at data center, row, or rack level.

Definition
The RCI provides a measure of the thermal conformance at the high (HI) end and at the low (LO) end of the selected temperature range. Specifically, RCI_{HI}=100% mean that no intake temperature is above the maximum recommended, and RCI_{LO}=100% mean that no intake temperature is below the minimum recommended.

$$RCI_{HI} = \left[1 - \frac{\sum_{x=1}^{n} (T_x - T_{max-rec})}{(T_{max-all} - T_{max-rec})n} \right] 100\,[\%] \quad (for\ T_x > T_{max-rec})$$

Where: T_x Temperature at equipment intake x
n Total number of intakes
$T_{max\text{-}rec}$ Max recommended intake temperature
$T_{max\text{-}all}$ Max allowable intake temperature

$$RCI_{LO} = \left[1 - \frac{\sum_{x=1}^{n} (T_{min-rec} - T_x)}{(T_{min-rec} - T_{min-all})n} \right] 100\,[\%] \quad (for\ T_x < T_{min-rec})$$

Where: T_x Temperature at equipment intake x
n Total number of intakes
$T_{min\text{-}rec}$ Min recommended intake temperature
$T_{min\text{-}all}$ Min allowable intake temperature

The *allowable* and *recommended* ranges provide guidance to operators on maintaining high reliability but yet operate their facilities in an energy efficient manner (ASHRAE 2004 and 2008, Telcordia 2001 and 2006). The recommended range is a statement of reliability. For extended periods of time, the IT-equipment manufacturers recommend maintaining the environment within these limits. The allowable range is a statement of functionality. These are the limits where equipment manufacturers test their equipment to verify that the equipment will function.

Required Input Data

- Equipment intake temperatures (representative subset)
- Selected equipment temperature specification (e.g., ASHRAE or NEBS)

Modeling specifics
Computational Fluid Dynamics (CFD) modeling can be used to establish all intake temperatures.

Measurement specifics
Intake temperature measurements must be taken close to the actual equipment intakes. The reading may be significantly different a few inches away from the intake openings.

Presentation of Results
The RCI™ is presented as two numbers: RCI_{HI} [%] and RCI_{LO} [%]

Interpretation
Using ASHRAE Class 1 temperature guideline (2008), <90% is often considered poor, ≥95% is often considered good, and 100% is ideal. An indication of potentially harmful conditions (temperatures outside the allowable range) is provided by a flag "*" appended to the RCI value, e.g., RCI_{HI}=95%*.

The proposed equipment intake temperature compliance chart shown in Figure 1 provides both a graphic representation and a metric representation of the compliance with a specific thermal specification such as ASHRAE or NEBS. Note that the intakes are arranged along the x-axis in order of increasing intake temperature. A similar chart will be used in Section 6 CFD Modeling Results.

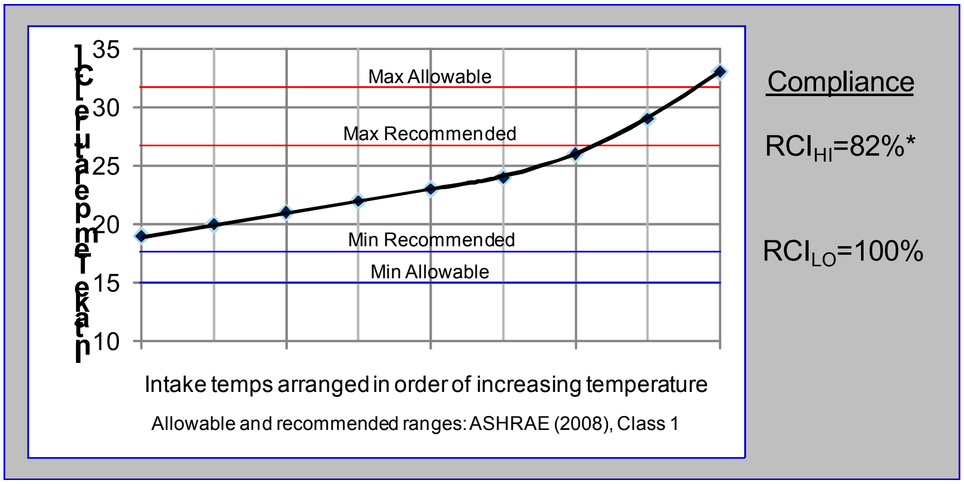

Figure 1: Proposed Intake Temperature Compliance Chart (Herrlin 2008a)

Capture Index (CI) (VanGilder and Shrivastava 2007) is a measure of the rack cooling performance based solely on airflow patterns.

Purpose
The CI is designed to quantify from where the rack intake airflow originated or to where the exhaust airflow traveled. The metric is a tool to understand the level of air mixing in the data center. The CI is typically a rack-level metric.

Definition
There are two variants of the CI: One for cold- and another for hot-aisle analysis. The cold-aisle variant is the fraction of air “ingested” by the rack that originates from local cooling resources (e.g., perforated floor tiles) whereas the hot-aisle variant is the fraction of air exhausted by a rack that is “captured" by local extracts (e.g., return vents).

Interpretation
CI is a number between 0 and 100%. Higher values generally imply better cooling performance. The metric is not easily measured experimentally but is readily computed based on CFD modeling.

Supply Heat Index (SHI) (Sharma et al, 2002) is a measure of recirculation of hot air into the cold aisle.

Purpose
The SHI is a dimensionless measure of recirculation of hot air into the cold aisle. This metric not only provide a tool to understand convective heat transfer in the equipment room but also suggest means to improve the energy efficiency; energy usage can be impacted by lack of air management that allows hot and cold air to mix. The metric can be used at data center, row, or rack level.

Definition

$$SHI = \left(\frac{\sum_j \sum_i \left((T_{in}^r)_{i,j} - T_{ref}\right)}{\sum_j \sum_i \left((T_{out}^r)_{i,j} - T_{ref}\right)}\right)$$

Where: *i* and *j* Racks and rows, respectively (e.g., i,j = 1,2 means rack 1 in row 2)
T_{in}^r Rack air intake temperature (assuming one air intake)
T_{out}^r Rack air exhaust temperature (assuming one air exhaust)
T_{ref} Reference (supply air into space) temperature

If the racks have more than one air intake/exhaust, "rack" means each air intake/exhaust opening.

Interpretation
The SHI is a number between 0 and 1, the lower the better. The SHI is typically < 0.40. An SHI = 0 means that all intake temperatures are equal to the supply temperature.

Return Temperature Index (RTI)™ (Herrlin 2008b) is a measure of room-level utilization of rack temperature rise as well as the level of net by-pass air or net recirculation air in the data center. The RTI is one of two high-level metrics used in the DOE Air-Management Tool. The RTI can be used in tandem with the RCI™ to ensure optimal operation. The two metrics encapsulate the effectiveness of the air management system as three non-dimensional numbers (RCI_{HI}, RCI_{LO}, and RTI).

Purpose
The RTI is a dimensionless measure of the actual utilization of the available temperature differential in the equipment room as well as a measure of the level of net by-pass air or net recirculation air in the data center. Both phenomena are detrimental to the thermal and energy performance of the facility.

Definition

$$RTI = \left(\frac{\sum_j w_{AC}(T_R - T_S)}{\sum_i w_{Rack}\Delta T_{Rack}}\right) * 100 = \left(\frac{\sum_i V_{Rack}}{\sum_j V_{AC}}\right) * 100[\%]$$

Where: *i* and *j* Specific racks and ACs, respectively
w_{AC} AC (air conditioner) airflow weighting factor
w_{Rack} Rack airflow weighting factor
T_R AC (air conditioner) return temperature
R_S AC (air conditioner) supply temperature
ΔT_{Rack} Temperature rise across rack
V_{Rack} Rack airflow rate
V_{AC} AC (air conditioner) airflow rate

If racks have more than one air intake/exhaust, “rack” means each air intake/exhaust opening.

Interpretation
A number above 100% suggests net air recirculation; a number below 100% suggests net by-pass air; cold air by-passes the IT-equipment and is returned directly to the air handler. An RTI of 100% mean balanced airflows and full utilization of the available temperature difference in the equipment room.

Recirculation Ratio (R) (Tozer et al 2009) is a measure of recirculation from equipment exhaust back to intake on the same piece of equipment.

Purpose
The Recirculation Ratio (R) is a measure of air recirculation. Recirculation is a significant contributor to hot spots in equipment rooms. The metric can be used at data center, row, or rack level.

Definition
The metric is defined as the ratio of the recirculation airflow to the total intake airflow. Ideally, the recirculation airflow should be zero. At the equipment room level, the Recirculation Ratio and the Bypass Ratio (see Section 3.2.1) can be viewed as a decomposition of the Return Temperature Index (RTI)™.

Interpretation
The metric is a number between 0 and 1. R=0 means no recirculation (ideal) and higher values mean more hot-air recirculation.

3.1.2 Research to Model Impact on the Thermal Environment: Placing High-Density Point Loads in Existing Telecom Switching Centers

More electronic equipment of the type historically found only in data centers is finding its way into telecom switching centers. This migration may lead to complications in terms of physical reliability. In 2006, therefore, Verizon Wireless took an initiative to perform research to better understand the related air-management issues by utilizing advanced computer modeling (Herrlin and Quirk, 2009).

The lack of separation of hot and cold air results in air mixing that leads to poor thermal and energy management. Although CFD modeling provides a wealth of information, sorting things out is often a tremendous challenge. Since the equipment environment is defined by the equipment intake temperatures, compliance with intake specifications is the ultimate thermal performance metric. The Rack Cooling Index (RCI)™ is such a metric.

By utilizing CFD modeling in tandem with the RCI metric, a large amount of data could be processed and presented in an understandable, objective, and standardized way. A well thought out plan for the analysis of high-density equipment is critical to ensure network availability and reliability. Air management tools are readily available today to develop strategies similar to those outlined in this ASHRAE Journal article.

3.1.3 Related Issue: Thermal Gradients in Data Centers after Cooling Outages

Optimal operation of cooling systems in data centers requires considering the energy cooling costs, the thermal equipment environment, *and* the space temperature response during cooling outages. Segregation of hot and cold air is one of the most effective ways of improving the energy efficiency. After a cooling outage, however, segregation may lead to thermal conditions that may jeopardize the functionality of the equipment. Since the equipment is on UPS power, it will continue dissipating heat during cooling outages.

Published work and additional modeling suggest steep gradients (PG&E, 2008). The more segregated the environment, the higher the severity. The initial gradient for fully enclosed equipment aisles is one order of magnitude higher compared to that for open architectures with no physical barriers. The time to reach the maximum *allowable* ASHRAE limit of 90°F from an initial temperature of 72°F may be on the order of seconds rather than minutes. Even at seemingly benign heat densities, the initial increase in temperature is alarming should the cooling system fail.

The short time to reach the maximum allowable ASHRAE limit should be taken very seriously. One key argument for enclosing aisles is the ability to operate the cold aisle near the maximum recommended temperature of 80°F, which deteriorates the thermal conditions further. Remedies may include putting fans and chilled-water pumps on UPS power.

3.2 Energy Management

Energy savings due to air management are related to increasing the supply air temperature and/or reducing the supply airflow rate. Different air management measures accomplish this to various degrees. The DOE Air Management (AM) Tool (DOE 2010) defaults to a 2% chiller energy saving for every °F increase in supply air temperature and a cubical relationship between fan energy and airflow. Consequently, relatively small airflow reductions can result in large energy reductions. In addition, elevated supply temperatures increase the chiller capacity; PG&E (2007) reports 30-50%.

The DOE AM Tool focuses on percentage energy savings for fans and chillers. The absolute energy savings (kWh) depend on the absolute energy for fans and chillers before the implementation of the air-management measures. The pie chart below shows typical power allocation in data centers. The allocation can vary significantly among data centers. The “other” slice includes power for a wide range of miscellaneous equipment located in the space depending on the particular data center.

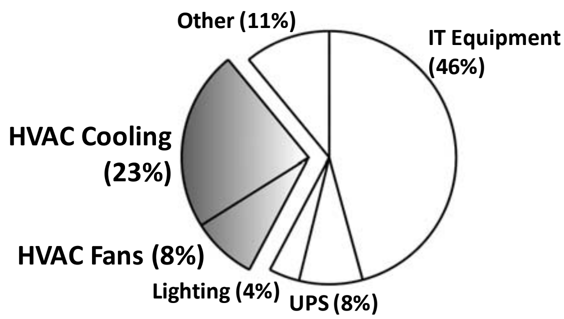

Figure 2: Typical Data Center Power Allocation according to LBNL.

Note that elevated supply air temperatures save energy at the chiller level but may increase the energy usage at the IT-equipment level. Generally, the server fans speed up above an intake temperature threshold to ensure adequate internal cooling, reducing the total savings (see Section 3.2.8).

The present study will look at different combinations of air management measures and estimate how much the supply airflow can be adjusted. When known, the energy savings can be estimated with the assumptions outlined above. The made assumptions are based on a number of case studies summarized below.

3.2.1 Engineered Air Management Energy Metrics

This section discusses energy metrics for air management in data centers, including purpose, definition, and interpretation.

Return Temperature Index (RTI)™ (Herrlin 2008) is a measure of room-level utilization of rack temperature rise as well as the level of net by-pass air or net recirculation air in the data center. See discussion under Section 3.1.1.

Bypass Ratio (BP) (Tozer et al 2009) is a measure of supply air by-passing the IT-equipment directly back to the air return of the air-conditioner.

Purpose

The BP is a measure of bypass air, which is a significant contributor to poor energy management in equipment rooms. The metric can be used at data center, row, or rack level.

Definition

The BR is the ratio of bypass airflow to supply airflow. The supply air is provided to the data center to cool the space. Ideally, the bypass should be zero. At the room level, the Recirculation Ratio (see Section 3.1.1) and the Bypass Ratio can be viewed as a decomposition of the Return Temperature Index (RTI).

Interpretation
The metric is a number between 0 and 1. BP=0 means no bypass air (ideal) and higher values mean more bypass air.

3.2.2 PG&E Data

The following information is taken from two recent reports from PG&E. The data indicate very large percentage energy savings for supply fans and more moderate percentage savings for chillers. Since chillers typically consume about three times the energy of supply fans (see Figure 2), the absolute savings are on the same order of magnitude. The savings due to supply fans and chillers combined are around 10% of the total data center energy and 20% if the IT-equipment energy is excluded. Note that the chiller savings due to air management are significantly boosted when an air-side economizer is present.

Data Center Air Management Report (PG&E 2007):

- "Air management (cold-aisle enclosures and VFD) reduced fan power by 75%"
- "CRAH capacity increased 30-49%"

High Performance Data Center: A Design Guidelines Sourcebook (PG&E, 2006):

- "Air management could result in a 20% energy saving on the chiller side"
- "With an airside economizer, air management can reduce cooling costs by over 60%"

The PG&E incentive program for data center airflow upgrades allows a number of air management measures, including those listed in Table 1. With more efficient airflow, supply air fans can be turned off (or down) and supply air temperatures can be increased. Both measures save energy. Potential energy savings are calculated from the estimated supply airflow reduction and the supply temperature increase, whereas the incentives are based on measured data.

Table 1 provides an estimate of the potential airflow "effectiveness" for different combinations of air management measures as measured by the Return Temperature Index (RTI)™. See Section 3.1.1 for a description of the RTI metric. This overall approach is similar to that in the DOE Air Management Tool (DOE 2010).

The PG&E incentive program includes data on 35 data centers. Nine of those have raised-floor cooling and sufficient data for statistical analysis. Typical fan energy savings are in the 40-50% range. The savings stem from installing blanking panels, strip curtains, re-arranging floor tiles, and turning selected CRAC units off. As expected, these savings are lower than for those in the Data Center Air Management Report discussed above (75%). VFD fans provide better tuning capabilities than simply turning units off as well as having a cubical relationship between energy reduction and airflow reduction.

Table 1: Effectiveness of Different Combinations of Air Management Measures as Measured by the Return Temperature Index (RTI)

	Return Temperature Index (RTI)™			
	25%	50%	90%	100%
Hot/cold aisle arrangement	X	X	X	X
Blanking panels		X	X	X
Perforated tiles in cold aisles only		X	X	X
End partition/curtain		X	X	X
Excess CRAC units OFF		X	X	X
Floor holes minimal			X	X
Partitions above racks			X	X
CFM matches Rack kW (VFD)				X
Set-point maximized				X

3.2.3 CISCO Data

CISCO conducted a study with the goal of confirming energy savings based on industry understandings related to raising the return air temperature and the supply chilled-water temperature set-points (CISCO 2009). The return temperature was raised in steps from 70°F to 80°F and the chilled-water temperature in steps from 44°F to 48°F. In conjunction with the study, they also introduced air-management best practices such as blanking panels and perforated floor tiles in cold aisles only. Measured values and supplemental computer modeling resulted in chiller cost savings of 13-21% associated with raising the air and water temperatures.

3.2.4 LBNL Data

Figure 3 shows measurements of a rather typical data center at Lawrence Berkeley National Laboratory (LBNL). Implementing air management could allow adjustments to the supply air temperature and airflow to render substantial energy savings.

Since the Return Temperature Index (RTI)™ is only 53%, the system airflow could ultimately be reduced by 47%. Due to the cubical relationship between fan power and fan flow, the fan energy could be reduced by around 85% (assuming VFD). In addition, the supply air temperature could potentially be increased by 15°F, which could translate into chiller energy saving of around 30% (LBNL 2007b). It is not untypical to see CRAC *return* air temperatures near those recommended for IT-equipment *intake* temperatures (shaded area in figure). It would be an understatement to say that air management is important for energy savings and cooling capacity management in this data center.

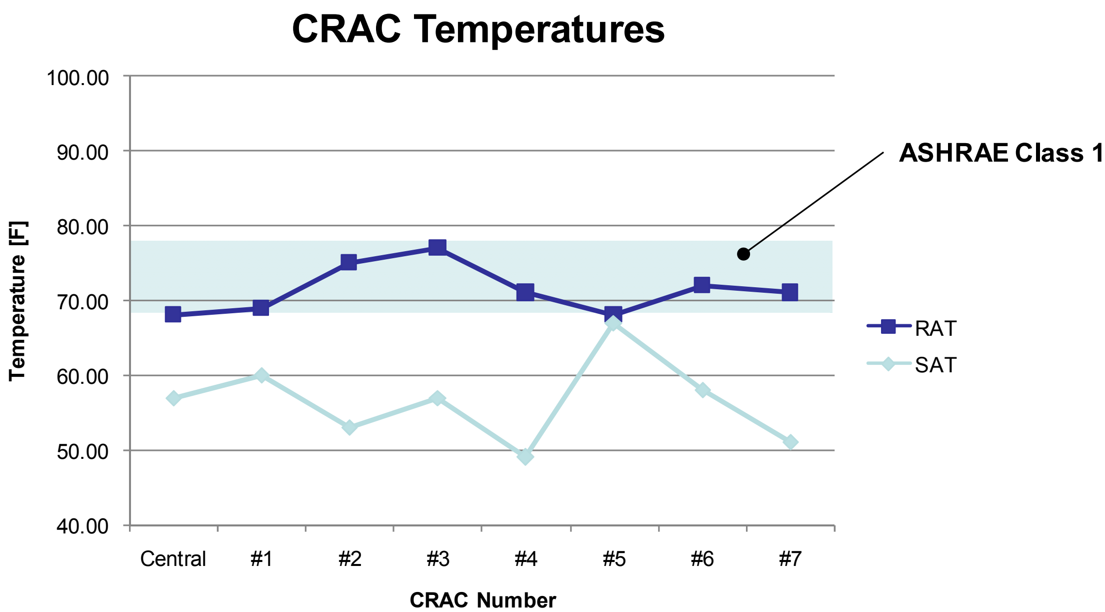

Figure 3: Measured supply (SAT) and return (RAT) temperatures for LBNL data center.

A demonstration of controlling computer room air handlers using wireless intake temperature sensors were performed by LBNL at the California Franchise Tax Board between August 2008 and April 2009 (LBNL, 2009). Additional best practices included re-arrangement of floor tiles, installation of variable frequency drives on supply fans, mounting of hot-aisle strip curtains, and filling empty rack positions with blanking panels. The controls software and hardware along with each best practice measure were installed sequentially and evaluated using a measurement and verification procedure between each upgrade. All in all, the fan energy was reduces by 66%; controls and software alone eliminated—somewhat surprisingly—60% of the fan energy and 14% of the chiller energy.

LBNL also provides technical best practices (LBNL, 2007a) for optimizing data center energy efficiency. The following list is the best practices for air management.

- Hot aisle/cold aisle
- Rigid enclosures
- Flexible strip curtains
- Blank unused rack positions
- Design for IT-equipment airflow configuration
- Select racks with good internal airflow
- Use appropriate diffusers
- Position supply and returns to minimize mixing and short circuiting
- Minimize air leaks in raised floor systems
- Optimize location of computer room air conditioners
- Provide adequately sized return plenum or ceiling height

- Provide adequately sized supply
- Use an appropriate pressure in under-floor supply plenums.

3.2.5 Stanford University Data

In 2009, Stanford University conducted a study: Satellite Server Rooms: How Efficient Are They? (Stanford 2009). Five equipment rooms were modified with different air management measures ranging from simple measures such as installing blanking panels to more costly such as installing VFD on supply fans. The measured supply temperature increase was in the range of 3°-11°F and the supply airflow reduction was in the range of 28-63%.

3.2.6 Intel Data

Typically, data center cooling devices use return air temperature sensors as the primary control-variable to adjust supply air temperature and airflow to the data center. A better approach is to control the data center air conditioning by using the built-in IT-equipment intake temperature sensors (Intel 2009). By matching needed equipment flow with actual CRAC flow, fan energy savings of 30-40% and greater can result. Supplying higher supply air temperatures significantly increase system efficiency; chiller energy savings of 20%-30% can be achieved. The project has already demonstrated and validated that IT-equipment can provide temperature information to the facility management system as well as use the server temperature readings to control cooling system operations with the facility management system. The next step will be to collect actual energy savings data.

3.2.7 Green Grid Data

In 2007, the Green Grid issued Guidelines for Energy-Efficient Data Centers (TGG 2007). The report outlines a framework for improving the energy efficiency of both new and existing data centers. The following list deals with air management issues.

- Hot-aisle/cold-aisle configuration
- Under-floor blockages
- CRAC placement
- Location of vented floor tiles
- Adequate number of vented floor tiles
- Matching airflows
- Eliminate mixing of cold and hot air
- Closely coupled cooling
- Blanking panels in racks
- Coordination of CRAC units.

3.2.8 Department of Energy (DOE) Air Management Tool

The Air-Management (AM) Tool is part of the DOE DC Pro software tool suite, which includes a web-based profiling tool as well as separate Excel-based assessment tools for cooling systems, air management, electrical systems, and IT-equipment (DOE 2010). They provide estimates of savings for various measures, but actual savings may vary based on site-specific conditions that are not addressed in the tools.

The AM Tool was developed to help accelerate energy savings in data centers without affecting the thermal IT-equipment environment. Based on user input, the Tool provides air management recommendations (actions) and the potential for reducing the supply airflow rate and increasing the supply air temperature. Finally, the Tool estimates the percentage energy reduction for supply fans and chillers. Note that the absolute savings depend on factors not covered in the Tool. Since the majority of conventional data centers have raised-floor cooling with hot and cold equipment aisles, the AM Tool is intended mainly for such environments.

Key factors for air management in the AM Tool are as follows:

- Aisle containment quality/implementation
- Blanking panels in and in between racks quality/implementation
- Floor sealing quality/implementation
- Tile/diffuser placement quality/implementation
- EC-Class (equipment ventilation protocol) quality/implementation
- Controls sophistication (RAT/IAT temperature sensing and CAV/VAV control)
- AHU modularity/distribution quality/implementation
- Cable/pipe management in supply air path quality/implementation.

Fan Energy: The following default assumptions are made for the relationship between fan energy and airflow. For Constant Air Volume (CAV) supply fans, turning units off is the only option in reducing the total airflow to the data center. Consequently, there will only be a linear relationship between energy and airflow. For Variable Air Volume (VAV) supply fans, turning units down results in a cubical relationship between energy and airflow.

Chiller Energy: It is assumed by default that a one degree (°F) increase of the supply air temperature will result in 2% chiller-energy saving due to more favorable operating conditions. The chiller-energy savings only takes into account the increase in supply air temperature, and additional savings from higher utilization of air-side economizers is not included.

Higher supply air temperatures may result in higher IT-equipment fan speed and, in turn, higher rack energy. Figure 4 shows rack and cooling energy as a function of server air inlet temperature and chilled-water supply temperature (Chill Off 2 2009). Not taking the variability in equipment fan speed into consideration may lead to sub-optimizations. The magenta curve shows the rack energy whereas the blue curve shows the cooling energy.

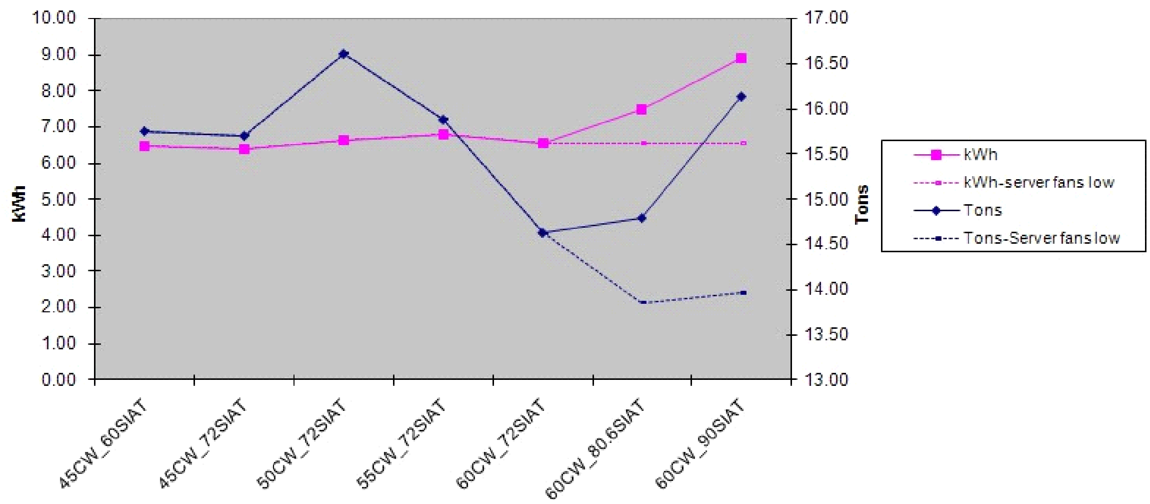

Figure 4: Rack Energy Increase Due to Equipment Fan Speed Increase at Higher Server Intake Air Temperatures

3.2.9 International Perspective: EU's Code of Conduct for Data Centers

The European Commission made public on October 30, 2008 a voluntary code of conduct for operating energy efficient data centers through adopting best practices. The aim of the Code of Conduct is to stimulate data centre operators to reduce energy consumption in a cost-effective manner without hampering the mission critical function of data centers. Parties signing up will be expected to follow the intent of the Code of Conduct.

The best practices for the Code of Conduct takes into account a number of simple measures that can reduce energy usage. Each practice has been assigned a qualitative value to indicate the level of benefit to be expected from an action and the relative priorities that should be applied to them. This supplement to the Code of Conduct is provided as an education and reference document to assist data center operators in identifying and implementing measures to improve the energy efficiency.

The objective of airflow management is to minimize by-pass air (no useful cooling) and recirculation air (elevated IT-equipment intake temperatures). Addressing these issues will deliver more uniform intake temperatures and allow temperature set points to be increased without the risk of equipment overheating.

The airflow management and design best practices include the following factors:

- Contained hot or cold air
- Blanking plates (empty equipment positions)
- Other openings (other paths in and around racks)
- Raised floor air flow management (cable cutouts)
- Return (ceiling) plenums
- Raised floor obstructions (cables)

- Hot/cold aisle
- Raised floor or dropped ceiling plenum height
- Equipment segregation
- Provide adequate free area on rack doors.

3.2.10 Similar Research to Model Impact on Energy Savings

An extensive internet search did not uncover any previous systematic research based on advanced computer modeling (CFD) for the energy impact of implementing combinations of air management measures. This finding makes the current study all the more important.

3.3 Summary of Section 3

3.3.1 Data Center Air Management Characteristics

Data centers are a diverse group of facilities, including the level of implementation of air management measures. Some data centers are designed and operated with no recognition of the importance of air management. Other data centers have implemented elaborative designs to perfect air management to increase energy efficiency, thermal conditions, and/or regain cooling capacity. Most data centers are somewhere in between these two extremes.

A summary based on twenty-two case studies and demonstration projects published by Tschudi and Fok (2007) pointed out that in data centers with lower than average cooling energy consumption many of the air management pitfalls were avoided. The better performing systems had been designed or modified to improve air management.

3.3.2 Air Management Measures

Based on the reviewed material, the following is a compilation of typical air management measures in data centers. The data was generally collected from organizations that did their own research to pinpoint effective air management measures. Since such research is based on multiple references, it provides significantly more information compared to the individual references it was based on.

- Use long parallel equipment rows
- Ensure hot and cold equipment aisles
- Use equipment with optimal ventilation schemes
- Install blanking panels in empty equipment positions
- Seal vertical gaps between equipment and rack enclosure
- Seal gaps between and under equipment racks
- Blank empty rack positions (no rack)
- Deploy aisle containment (top and/or sides)
- Deploy ducted return
- Seal raised floor systems (cutouts, tiles)
- Locate perforated floor tiles to cold aisles only
- Use adequate number of perforated floor tiles

- Locate ceiling returns to hot aisles
- Use (correctly sized) return air plenum
- Use adequate ceiling height
- Install CRAC chimney to increase return temperature
- Coordinate CRAC supply temperatures
- Use Variable Frequency Drive (VFD) on supply fans
- Implement equipment intake temperature control
- Ensure proper CRAC modularity, distribution, and orientation
- Use appropriate pressure level in raised-floor plenum
- Ensure unobstructed floor plenums
- Segregate equipment with non-optimal ventilation schemes
- Provide adequate free area on equipment rack doors.

These measures contribute to less mixing of hot and cold air that help realize the ultimate goal of air management; namely, minimizing the supply airflow and maximizing the supply temperature. Some of these measures can be categorized as design measures, which can be difficult to incorporate in existing facilities.

Finally, note that over-head air distribution or under-floor air distribution is not an air-management measure since each system works adequately with proper design. Besides, it is generally not cost effective to convert one system into the other. Note also that "minimize mixing of hot and cold air" or "use matching airflows" is not a *measure* but rather a desirable *result* enabled by one or several air management measures.

3.3.3 Energy Savings Due to Air Management

Table 2 is a summary of realized or estimated fan and chiller energy savings for the reviewed case studies and tools. Note that the numbers in *italics* are ANCIS estimates to complete the table. It is not always clear what measures that were implemented. At a minimum, however, these savings suggest the magnitude of savings for air management.

The fan energy savings can be very high for certain measures such as equipment aisle enclosures with VFD supply fans. Fan savings in the 70-90% range and chiller savings in the 15-25% range are achievable (~35% savings on HVAC energy). The PG&E incentive program material has fan savings in the range of 40-50%. The lower savings for these data centers can be contributed to constant air volume fans. Finally, the DOE Air Management Tool suggests typical fan energy savings of 60-80% and chiller energy savings of 15-20%.

In addition to energy savings, air management measures can also lead to improved thermal conditions for the IT-equipment. Indeed, in many cases, thermal management is the driver rather than energy management.

Table 2: Realized or Estimated Energy Savings for Selected Case Studies and Tools (for implemented measures, see footnotes)

	FAN			CHILLER		
Study	**Airflow Reduction [%]**	**Reduction Exp. ( )^x [-]**	**Energy Savings [%]**	**Supply Air Temp Increase [°F]**	**Energy Reduction [%/°F]**	**Energy Savings [%]**
PG&E[1]	37	3	75	-	-	-
PG&E[2]	40-50	1	40-50	-	-	-
Cisco[3]	-	-	-	10	-	13-21
LBNL[4]	47	3	85	15	2	30
LBNL[5]	*27*	*3*	60	*7*	*2*	14
Stanford[6]	28-63	*3*	*63-95*	3-11	*2*	*6-22*
Intel[7]	11-16	3	30-40	10-15	2	20-30
DOE[8]	26-43	3	59-82	8-10	2	16-20

Footnotes:

1) Data Center Air Management Report (PG&E 2007)
    - Cold aisle enclosure and VFD supply fans
    - Measured values
2) Data from PG&E's air management incentive program
    - Blanking panels, strip curtains, floor grill re-arrangement, and shutting down selected CRAC units
    - Measured supply and return air temperatures (to estimate energy reduction)
3) Lab Energy Savings: DCSTG Lab Temperature Set-Point Increase (CISCO 2009)
    - Blanking panels and floor grill re-arrangement
    - Measured and modeled values
4) Baseline CFD Model of LBNL Data Center 50B-1275 (LBNL 2007b)
    - Estimated maximum reductions based on measurements
5) Demonstration of Datacenter Automation Software and Hardware at the California Franchise Tax Board (LBNL 2009)
    - IT-equipment intake sensing, adjust floor tiles, air curtains, blanking panels, and VFD supply fans
    - Measured values due to controls and software only
6) Satellite Server Rooms: How Efficient Are They? (Stanford 2009)
    - Five rooms with different measures from blanking panels to VFD
    - Measured values
7) Control of Computer Room Air Conditioning using IT Equipment Sensors (Intel 2009)
    - IT-equipment intake sensing and VFD supply fans
    - Estimated savings potential
8) DOE Air Management Tool (DOE 2010)
    - Excel-based simulation tool
    - Estimated typical potential

4. DATA CENTER MODEL SPECIFICATION

Introduction

The purpose of this section is to develop a detailed specification for the representative or prototypical data center. The specification will be used for the parametric Computational Fluid Dynamics (CFD) modeling and will be based on available data on data centers, including those listed in Section 3. Specifically, the purpose of this section is as follows:

- Establish the representative data center utilized for the CFD modeling, including the computational sub-domain; size, layout, and equipment; and physical characteristics of eight air-management measures and their three quality/implementation levels.

- Describe the main numerical model assumptions such as mesh size and conditions at the limits of the sub-domain.

4.1. Computational Sub-Domain

Selecting the numerical computational sub-domain requires striking a balance between detail and overview. It should be small enough to allow detailed analysis of near-rack airflow but large enough to allow analysis of large-scale airflow patterns in the equipment space.

The sub-domain is a section of the data center defined by utilizing symmetry planes, which assume a mirror image of the environmental conditions on the other side of each plane. The sub-domain is not only the size but also the overall layout and type of IT and HVAC equipment. The air-management measures will be addressed in section 4.2, which will complete the description of the representative data center.

Figure 5 shows a plan drawing of the computational sub-domain. It utilizes three symmetry planes as well as adiabatic walls, ceiling, and floor. The computational mesh size was between 600,000 and 900,000 grid cells, which resulted in effective solution of the conservation equations of continuity, momentum, and energy. The blue rectangular boxes represent the parallel IT-equipment lineups whereas the gray boxes represent the CRAC units. Note that only one-half of the outer two units are shown due to the symmetry planes.

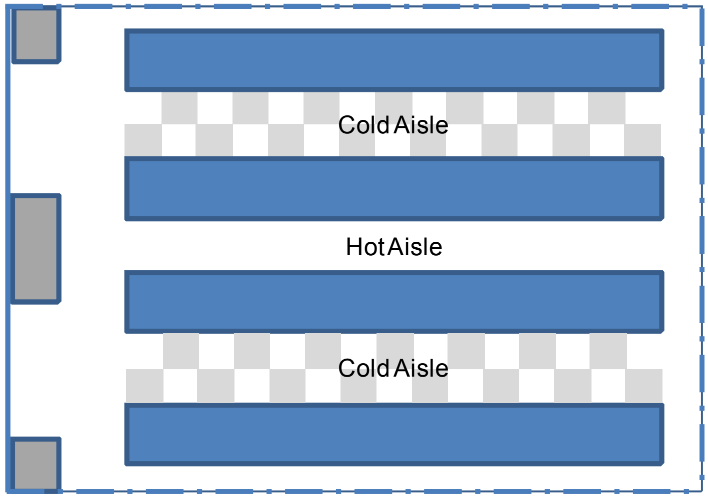

Figure 5: Computational sub-domain, plan drawing (1066ft^2).

Below is an in-depth description of the computational sub-domain.

- Overall size:
  - Length and width: 39’-0” (468”) and 27’-4” (328”) (1066 ft^2)
  - Height from raised floor: 11’-0”
  - Raised-floor height: 2’-0” (under-floor cooling and cabling)

- Floor layout:
  - Four (4) equipment lineups with fifteen (15) racks each (30 ft)
  - Hot and cold aisles
  - Cold/hot aisles widths: 4ft/3ft
  - Two (2) down-flow CRAC units (one full unit + two ½ units)
  - Perforated tiles: 1) Thirty (30) or 2) sixty (60) 25% open
  - Return air paths: Free return.

- IT-equipment racks:
  - Heat densities: 1) 80 W/ft^2 (“typical”) and 2) 160 W/ft^2
  - Heat release: 1) 1440 W/rack or 2) 2880 W/rack
  - Delta-T: 27°F (15°C)
  - Airflow: 1) 168 cfm or 2) 336 cfm with front-to-rear (F-R) cooling
  - Equipment size (w-d-h): 24”-40”-78”

- CRAC units
  - Delta-T: Units can match IT-equipment delta-T
  - Supply air temperature: Tables 6 and 7
  - Airflow: Calculated to meet intake temperatures specification (RCI=95%)
  - Unit size (w-d-h): 99”-36”-72”

Each IT-equipment rack is modeled as six (6) individual equipment shelves to capture vertical temperature gradients and to accurately calculate the Rack Cooling Index (RCI)™. Each of the six shelves has its own intake, exhaust, airflow, and heat release.

4.2. Air-Management Measures

The air-management specifications for the sub-domain are shown in Tables 3 and 4. The listing starting before the tables includes descriptions of all measures included in the two tables. These measures were selected as prime candidates for inclusion in the parametric analysis. Note that these measures are a subset of those identified in Section 3.3.2 as well as being identical to those used into the DOE Air Management Tool.

Note that in Table 3, "No panels" or "No floor sealing" are not relevant quantitative descriptions since it may be perfectly fine if there is very little vacant rack space or very few floor penetrations. The introduced open area and leakage (Table 4) are better indicators of air-management performance. As such, they will be used for the analysis. Each of the air management measures included in Tables 3 and 4 are briefly described below. These descriptions are not intended to be all inclusive. Section 5 will select the measures and groupings of measures for the study.

<u>Aisle containment</u>

Aisle containment is an effective way of separating hot and cold air in the data center. Physical barriers, however, often require accurate airflow controls with VFD fans. Full or partial containment can be implemented by either enclosing the cold or hot aisles with either flexible strip curtains or rigid barriers.

<u>Blanking panels</u>

Blanking panels cover openings between the hot and cold aisles. Any openings between these aisles contribute to air mixing by recirculation air, by-pass air, or both. Any unused vertical positions in equipment racks should be filled with blanking panels. Other common leakage paths occur between the equipment shelves and the vertical rack posts as well as between the equipment racks.

<u>Floor sealing</u>

Unsealed cable penetrations in the raised floor can contribute to a significant leakage. The fact that most penetrations are located towards the rear of the IT-equipment, such leakage often results in by-pass air, which does not contribute to cooling the equipment but rather goes directly back to the air handler. Additional floor leakage occurs along tile seams, along walls and around columns, and around CRAC units and PDUs. The specified leakage in Table 4 is valid for 80W/ft^2. At higher heat densities, the percentage leakage will be reduced since more perforated floor tiles will be required.

Table 3: Qualitative description of air-management quality levels

Measure	Low (1) Quality	Mid (2) Quality	High (3) Quality
1. Aisle containment	No containment	Doors to cold aisles	Full containment of cold aisles
2. Blanking panels	No panels	Mixed quality and/or implementation	All panels
3. Floor sealing	No floor sealing	Mixed quality and/or implementation	Extensive floor sealing
4. Tile placement	Many tiles outside cold aisles	Some tiles outside cold aisles	No tiles outside cold aisles
5. EC-Class	Many racks with other than F-T/R Class	Some racks with other than F-T/R Class	Front-to-Top/Rear (F-T/R) Class
6. Controls	Return air sensing and CAV fans	Return air sensing and VAV fans	Intake air sensing and VAV fans
7. AHU modularity	Low modularity and away from loads	Mixed modularity and proximity	High modularity and near loads
8. Cable management	Many obstruction in air path	Some obstruction in air path	No or little obstruction in air path

Table 4: Quantitative description of air-management quality levels (Items in clear cells are included in modeling)

Measure	Low (1) Quality	Mid (2) Quality	High (3) Quality
1. Aisle containment	No containment	Doors to cold aisles (2” gaps)	Full containment of cold aisles (1” gaps)
2. Blanking panels	Open area of total front rack area: 20%	Open area of total front rack area: 8%	Open area of total front rack area: 2%
3. Floor sealing	Floor leakage: 50% of total @80W/ft^2	Floor leakage: 25% of total @80W/ft^2	Floor leakage: 10% of total @80W/ft^2
4. Tile placement	Tiles outside cold aisles: 20% of total	Tiles outside cold aisles: 10% of total	Tiles outside cold aisles: 0% of total
5. EC-Class	Non-optimal: 15% other than F-T/R	Non-optimal: 8% other than F-T/R	All-optimal F-T/R Class
6. Controls	Return air sensing and CAV fans	Return air sensing and VAV fans	Intake air sensing and VAV fans
7. AHU modularity	Each CRAC/H serves 60 racks	Each CRAC/H serves 30 racks	Each CRAC/H serves 15 racks
8. Cable management	Blockage: 30% of total cavity volume	Blockage: 20% of total cavity volume	Blockage: 10% of total cavity volume

Tile placement

The perforated floor tiles should only be placed in the cold equipment aisles and approximately match the IT-equipment airflow needs. Placement in other locations (hot aisle or cross aisles) results in by-pass air and degraded operating conditions. There is no need to “cool down” the hot aisles by placing perforated floor tiles in those aisles; the hot aisles are supposed to be hot. The exit velocity from the perforated floor tiles is assumed to be within the manufacturers’ recommended range.

EC-Class

Equipment-Cooling (EC) Classes describe where cooling air enters and leaves the equipment rack envelope (Telcordia, 2001). Optimal EC-Classes support the desirable hot and cold aisle layout. A front-to-rear (F-R) ventilated rack is considered an optimal Class since it moves air from the cold aisle to the hot aisle. Non-optimal equipment is best taken care of by zoning the equipment space.

Controls

Return air temperature sensing and Constant Air Volume (CAV) fans is the norm although it cannot guarantee low energy usage or adequate equipment intake conditions. Return air sensing and Variable Air Volume (VAV) fans provide better energy management but cannot guarantee adequate intake conditions. Intake air temperature sensing and VAV fans provide the best operating conditions, both from an energy and thermal stand point.

AHU modularity

Modularity of the air handlers and proximity to the heat loads also determine how effectively the IT-equipment can be cooled. High modularity may be a prerequisite to placing the air handlers near the heat-generating IT-equipment. For example, using two smaller air handlers rather than one large may result in better equipment cooling.

Cable management

Cable management is about minimizing the obstructions in the airflow path in the raised floor. Heavily loaded floor plenums reduce the total delivered airflow volume and skew the airflow distribution. Combined, adequate cooling of individual racks cannot be guaranteed. Cable management includes using cable raceways and “mining” of unused cables.

The AM Tool groups the eight measures into four categories, each assigned three quality levels (Low (1), Mid (2), and High (3)).

"Airflow Blockers"
- Aisle containment
- Blanking panels
- Floor sealing

"Airflow Drivers"
- Perforated tile/diffuser placement
- EC-Class (IT-equipment ventilation protocol)

"Airflow Delivery"
- Controls sophistication
- AHU modularity/distribution
- Cable/pipe management

These groups of physically related measures were introduced to make the design of the Air Management Tool's lookup tables more manageable and the fact that there was not much granular data available. Table 5 shows the look-up table at the Mid (2) level of quality for the "Airflow Delivery" grouping, since this level will be assumed in the present study.

Table 5: Look-up tables in the DOE Air Management Tool (Delivery=Mid (2)); Assumes ASHRAE (2008) recommended temperature range of 64.4° – 80.6°F.

Blockers	**Drivers**		
Airflow Ratio [-]	**Low (1)**	**Mid (2)**	**High (3)**
Low (1)	2.7	2.1	1.7
Mid (2)	2.1	1.7	1.3
High (3)	1.7	1.3	1.2
Supply Air Temp [°F]	**Low (2)**	**Mid (2)**	**High (3)**
Low (1)	63	66	68
Mid (2)	66	70	72
High (3)	68	72	74

The table shows the airflow ratios or the excess airflow required from the air handlers to maintain an RCI_{HI} of 95% at the assumed supply air temperatures. For example, 2.0 means that the air handlers need to supply twice the airflow drawn into the IT-equipment to compensate for poor air management. To allow a direct comparison with the DOE Air Management tool, this study will also assume the supply air temperatures in Table 5. Thus, the focus is on reducing airflow *and* increasing supply air temperature.

5. MEASURES and MEASURE GROUPINGS

Introduction

In the previous Section 4, various air management measures were discussed. In this Section, we will select the measures and the groupings of measures that will be used for the parametric computer modeling.

5.1. Selection of Measures

Table 6 shows the air-management measures to be applied to the sub-domain. Measures 1-4 were selected to be included in the parametric analysis: Aisle containment, blanking panels, floor sealing, and perforated tile placement. Fixed values will be used for the remaining measures (5-8) throughout the modeling as indicated in the table.

The IT-equipment was assigned an optimal EC-Class (3) except for Case 1. The Controls measure assumes intake temperature sensing and VAV fans (3). Controls with return air temperature (RAT) sensing and CAV fans (1) will always result in higher airflow rates and depend on a number of factors, including the CRAC modularity. Finally, the Mid level (2) was selected for the AHU and Cable measures.

5.2. Selection of Groupings

The next step in defining the parametric modeling is to select the groupings of the four selected measures. The selection will be limited to eleven (11) permutations as shown in Table 6. They were selected to include PG&E's priorities and a wide range of data in the look-up tables of the DOE Air Management Tool (see Table 5). The assumed order of implementation is tile placement → floor sealing → blanking panels → containment.

Table 6: Selected air management measures and groupings of quality levels; See Table 4 for descriptions of quality levels 1, 2, and 3.

Measures	**Groupings of Quality Levels** (x-x indicates averages for Blockers (measures 1-4) and Drivers (measures 4-5))										
	1-1 #1	**1-2 #2**	**1-2.5 #3**	**Extra 1-3 #4**	**1-2.5 #5**	**Base 2-2.5 #6**	**2-2.5 #7**	**2-3 #8**	**2-3 #9**	**3-3 #10**	**3-3 #11**
1.Containment	1	1	1	1	1	1	2	2	2	2	3
2.Blanking panels	1	1	1	1	1	**2**	2	**2**	2	**3**	3
3.Floor sealing	1	1	1	1	2	**2**	2	**2**	3	**3**	3
4.Tile placement	1	1	2	3	2	**2**	2	**3**	3	**3**	3
5. EC-Class	1	3	3	3	3	3	3	3	3	3	3
6. Controls	3	3	3	3	3	3	3	3	3	3	3
7. AHU	2	2	2	2	2	2	2	2	2	2	2
8. Cable	2	2	2	2	2	2	2	2	2	2	2
SAT [°F]	63	66	67	68	67	71	71	72	72	74	74

The permutations shown in Table 6 map the excess airflow range of 1.2-2.7 in the AM-Tool look-up table in Table 5 (the total range for all three look-up tables is 1.0-2.9); worst and best values in the look-up table are included. The selection may also provide some insight into whether the groupings in the AM-Tool are accurate; four data points are calculated twice with different input. The fact that “Drivers” lean towards Mid (2) or High (3) before changes are made to “Blockers” is also reflected in Table 6.

Note that the x-x numbers in the column headings of Table 6 will be used to find the corresponding airflow and supply air temperature suggested by the DOE Air Management Tool. For example, 1-2 (second column in Table 6) results in access airflow of 2.1 in Table 5 (Blocker=1 and Driver=2). If the modeling results in a significantly different airflow, the value in the look-up table may need to be changed.

The quality levels (1-3) of the four first measures in Table 6 will be altered while the remaining four measures will be kept constant at the indicated quality levels. The only exception is Case 1, which has an EC-Class of Low (1) quality to produce the upper-left corner point in Table 5 with a value of 2.7. The symmetrical pattern in Table 6 is interrupted only by the Extra Case 4, which was introduced to include the upper-right corner point with a value of 1.7. Case 11 represents the lower-right corner point with a value of 1.2. The lower-left corner point is not included in the modeling since it is a highly unlikely combination of measures.

Note that there is no direct match between the PG&E groupings in Table 1 and those in Table 6. PG&E’s RTI=25%, 50%, 90%, 100% do not fit readily into Table 6 since its definition is different. PG&E asked whether measure were implemented or not whereas this study asks at what relative level they are implemented (see Section 4.2).

5.3 Additional Modeling

In addition to the eleven permutations shown in Table 6, an additional three modeling cases are outlined in Table 7. The base case from Table 6 is also selected as a reference for this additional analysis; the selected Case 6 is near the middle of Table 6. These additional modeling cases are snap shots of the impact of three changes to the data center rather than systematic permutations.

The additional modeling covers three changes:

- Constant Air Volume (CAV) air handlers can only reduce airflow by turning select units off. Depending on how many units serve one particular area, the granularity can be anything from poor to good. Turning select units off rather than turning all down, the airflow distribution is often adversely affected. There are two units in the computational sub-domain. The middle (full) unit will be turned off.

  The base case in Tables 6 and 7 assumes VAV fans where both units are adjusted to meet RCI=95%. The next step is to supply the combined airflow from only one

CAV unit and study the reduced RCI performance due to less effective air distribution—if any. The assumption here is that the single operating CAV unit perfectly matches the combined airflow. So, the focus is on air distribution challenges rather than imperfectly matched airflows.

- Rather than allowing the hot exhaust air to freely find its way back to the top of the air handlers, a ceiling plenum can be used to reduce the potential mixing of hot and cold air. In this modeling case, a ceiling plenum is introduced with a number of returns placed directly over the hot aisles.

- Many modern data centers have areas with higher-than-average heat densities. The impact on the required excess supply airflow (over the equipment airflow) to provide intake temperatures within specifications will be studied by increasing the heat density from 80 W/ft^2 to 160 W/ft^2. To accomplish this, the equipment power and airflow is increased by a factor of two. The number of perforated floor tiles in the cold aisles is also doubled to accommodate the higher airflow requirement.

Table 7: Additional modeling based on selected conditions (spot checks); See Table 4 for descriptions of quality levels 1, 2, and 3.

Measures	**Groupings of Quality Levels**			
	Base (2-2.5) #6	**CAV #12**	**Ceiling Plenum #13**	**Heat Density #14**
1.Containment	1	1	1	1
2.Blanking panels	2	2	2	2
3.Floor sealing	2	2	2	2
4.Tile placement	2	2	2	2
5. EC-Class	3	3	3	3
6. Control	3	CAV fans	3	3
7. AHU	2	2	2	2
8. Cable	2	2	2	2
Ceiling Plenum	No	No	**Yes**	No
Heat Density	80	80	80	**160**
SAT [°F]	71	71	71	**71**

6. CFD MODELING RESULTS

Introduction

In Sections 4 and 5, we established the data center model specifications, the air management measures, and the groupings of those measures that will be used for the computer modeling. In this section, the Computational Fluid Dynamics (CFD) modeling results will be discussed.

6.1. Modeling Focus

Ensuring adequate equipment intake conditions as measured by the Rack Cooling Index (RCI)™ can be accomplished by either increasing the supply airflow and/or lowering the supply air temperature. However, to allow a direct comparison with the DOE Air Management (AM) Tool, the supply temperatures were fixed to those values used in the tool per Table 5 in Section 4.2. Only the airflows will be adjusted to ensure adequate rack intake temperatures. In other words, the optimal airflow at a fixed supply temperature will be determined. However, this is not an optimization of both supply airflow and supply temperature that would results in the lowest HVAC energy usage. That would have entailed a much larger study scope (see Section 9).

6.2. Modeling Assumptions

Although the modeling assumptions are discussed in detail in Sections 4 and 5, the following bullets highlight some of the key assumptions.

- <u>Recommended and Allowable Intake Air Temperatures.</u> The ASHRAE (2008) Thermal Guidelines specification for "Class 1" typical data center environments is used for operating the data center and also for calculating the Rack Cooling Index (RCI). The recommended range is 64.4°−80.6°F and the allowable range is 59.0°−89.6°F. These levels are shown in Figure 6 as horizontal red and blue lines.

- <u>RCI Target Value.</u> The target RCI_{HI} value in this study is 95%; the emphasis is on conforming to the *maximum* recommended and allowable intake temperatures. Figure 6 illustrates this target level where the intakes have been arranged along the x-axis in order of increasing intake temperature. The red triangular area is 5% of the total area between the Maximum Allowable (Max All) and the Maximum Recommended (Max Rec) red lines. The RCI values/graphs were calculated and drawn by the RCI Software (ANCIS 2010).

- <u>Ideal Controls.</u> Since IT-equipment intake temperature sensing combined with VAV fans is assumed for all cases, the computer modeling provides the *potential minimum* or "achievable" supply airflow required at the fixed supply temperature. Actual results will depend on the implementation of these types of controls. Other types of controls result in over provisioning of supply air; the airflow can be significantly higher than those calculated in this study.

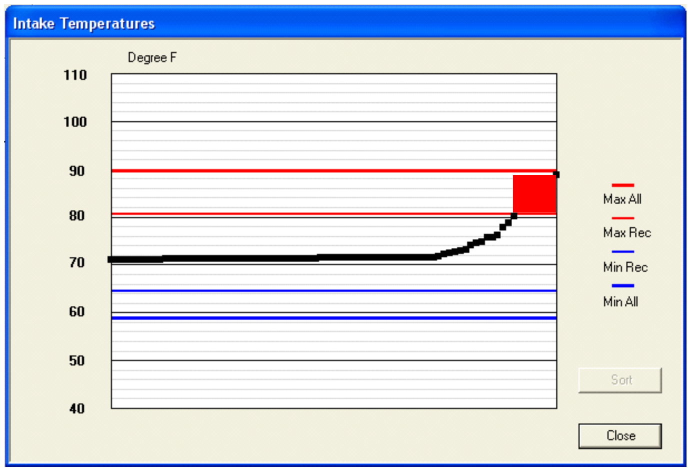

Figure 6: Example of RCI_{HI}=95% as drawn by the RCI™ Software (ANCIS 2010). The intakes have been arranged along the x-axis in order of increasing intake temperature.

6.3. Modeling Results

Tables 8 and 9 summarize the modeling results followed by a discussion on each of the ten modeling cases. Please refer to these tables and Table 4 in Section 4.2 to better understand the physical changes or air management measures implemented between the different modeling cases. In Appendix 1, there are temperature plots for each of the ten modeling cases similar to the example plot shown in Figure 6. The entity 100/RTI is the ratio between CRAC airflow and IT-equipment airflow.

Table 8: Selected air management measures and groupings of quality levels as well as key results from the CFD modeling (yellow rows). Cases in red were excluded. RAT = CRAC Return Air Temperature; IAT = Rack Intake Air Temperature.

Measures	**Groupings of Quality Levels** (x-x indicates averages for Blockers (measures 1-4) and Drivers (measures 4-5))										
	1-1 #1	**1-2 #2**	**1-2.5 #3**	**1-3 #4**	**1-2.5 #5**	**Base 2-2.5 #6**	**2-2.5 #7**	**2-3 #8**	**2-3 #9**	**3-3 #10**	**3-3 #11**
1.Containment	1	1	1	1	1	1	2	2	2	2	3
2.Blanking panels	1	1	1	1	1	2	2	2	2	3	3
3.Floor leakage	1	1	1	1	2	2	2	2	3	3	3
4.Tile placement	1	1	2	3	2	2	2	3	3	3	3
5. EC-Class	1	3	3	3	3	3	3	3	3	3	3
6. Controls	3	3	3	3	3	3	3	3	3	3	3
7. AHU	2	2	2	2	2	2	2	2	2	2	2
8. Cable	2	2	2	2	2	2	2	2	2	2	2
SAT	63	66	67	68	67	71	71	72	72	74	74
100/RTI @ 95%	1.14	1.30	1.40	N/A	N/A	1.86	1.70	1.72	N/A	1.45	1.20
RAT [°F]	87.4	87.3	86.8	N/A	N/A	86.0	87.4	88.2	N/A	93.0	96.7
Average IAT [°F]	72.1	73.9	74.4	N/A	N/A	74.0	74.3	74.7	N/A	76.2	76.5

Originally, the selection of the groupings of the four air management measures included all eleven cases shown in Table 8. They were selected to include PG&E's priorities and a wide range of data in the look-up tables of the DOE Air Management Tool. In the final selection of groupings, however, Cases 4, 5, and 9 were excluded (highlighted in red).

In addition to the cases shown in Table 8, three additional modeling cases were originally outlined per Table 9. Base Case 6 is used as the reference case for the additional cases. In the final selection of groupings only two cases were included (Cases 12 and 14).

Table 9: Additional modeling based on selected conditions as well as key results from the CFD modeling (yellow rows). Case in red was excluded.

Measures	**Groupings of Quality Levels**			
	Base (2-2.5) #6	**CAV #12**	**Ceiling Plenum #13**	**Heat Density #14**
1.Containment	1	1	1	1
2.Blanking panels	2	2	2	2
3.Floor leakage	2	2	2	2
4.Tile placement	2	2	2	2
5. EC-Class	3	3	3	3
6. Control	3	CAV fans	3	3
7. AHU	2	2	2	2
8. Cable	2	2	2	2
Ceiling Plenum	No	No	**Yes**	No
Heat Density	80	80	80	160
SAT	71	71	71	71
100/RTI @ 95%	1.86	1.86	N/A	1.47
RAT	86.0	86.0	N/A	89.7
Average IAT	74.0	74.2	N/A	73.4

Cases 6-8 and 10-11

Case 6 is the Base Case or reference case. The cross section in Figure 7 shows how a typical equipment aisle is filled with cold (blue) air from the bottom up. The conditioned air is supplied into each cold aisle via fifteen perforated floor tiles along the entire length of the aisle (see Figure 5 in Section 4.1). As with most raised-floor cooling systems, there is a distinct interface between cold air and hot air towards the top of the equipment racks. This interface needs to be high enough to ensure an RCI_{HI}=95%. The figure also points out that air flows *out* from the cold aisle through the mid-height gaps (empty shelves) in the racks. The static pressure is higher in the cold aisle due to the higher density of the cold, dense air. The floor leakage (cable penetrations) behind the racks is clearly visible.

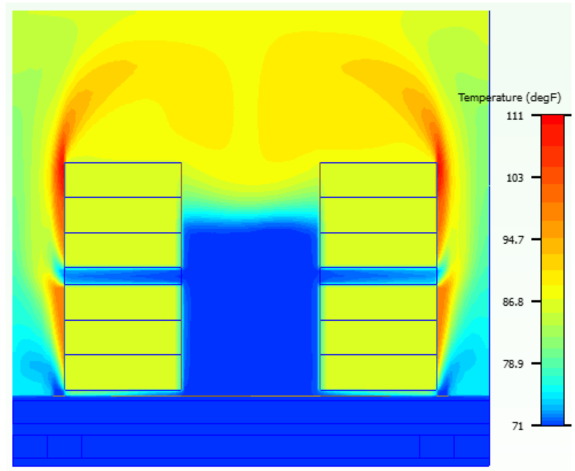

Figure 7: Temperature plot of Base Case 6;
cold air is leaving the cold aisle through the mid-height gaps.

For **Case 7**, strip curtains are added to the ends of the cold aisles. The curtains reduce the aisle end effect (i.e., infiltration of ambient air) and there is less need for supply airflow to ensure adequate IT-equipment intake conditions. The 100/RTI (the ratio between CRAC airflow and rack airflow) is reduced from 1.86 to 1.70 (-9%). Thus, the return air temperature increases.

For **Case 8**, "stray" tiles in the cross aisle are removed and the supply temperature is increased from 71° to 72°F. Since there are strip curtains, the removal of the stray tiles should have just marginal impact. The slightly increased need for supply airflow (1.70 → 1.72) is due to the increased supply temperature.

For **Case 10**, three things are changed compared to Case 8: First, better implementation of blanking panels; second, better implementation of floor tightening; third, an increase of the supply temperature from 72° to 74°F. The results show that the first two measures far outweigh the third measure, and the need for supply air as expressed by the 100/RTI decreased from 1.72 to 1.45.

For **Case 11**, full aisle enclosure with only marginal leakage is added to the previous case. The segregation of cold and hot air is now at its best, and the need of supply air is decreased further (1.45 → 1.20). Only 6% of the cold air supplied directly into the cold aisles leaks out (see Figure 8). The reduced supply airflow and the elevated supply air temperature push the return air temperature to 96.7°F.

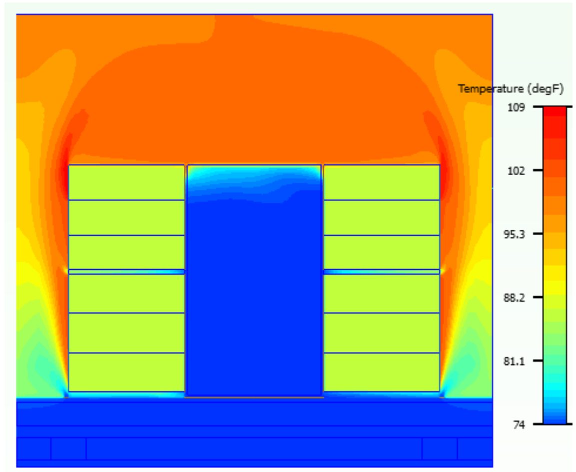

Figure 8: Temperature plot of Case 11; state-of-the-art segregation of cold and hot air.

<u>Cases 12 and 14</u>

For **Case 12,** Constant Air Volume (CAV) fans replace the Variable Air Volume (VAV) fans in Case 6. However, the modeling results show no change in required airflow compared to the base case. This implies that the new *airflow distribution* did not negatively impact the intake temperatures. However, a CAV system cannot guarantee a match between the airflow from the air-handlers and the airflow ingested by the load since it depends on the modularity of the CRAC units. In a CAV system, the total airflow can only be reduced in discrete steps by turning CRAC units off. This procedure often results in a significant over-provisioning.

For **Case 14**, the heat density is increased from 80 W/ft^2 to 160 W/ft^2 compared to Case 6. The *relative* airflow required through the perforated tiles (relative to the rack airflow) is reduced compared to the base case, which can be contributed to the uniform air supply along the cold aisles that tends to guard against infiltration of ambient air. In the cold aisles, all floor tiles are now perforated rather than every other. Also, the *relative* floor leakage is reduced since the number of perforated tiles is doubled but the *absolute* floor leakage remains unchanged. The net effect is that the flow ratio 100/RTI is reduced significantly from 1.86 to 1.47 and as a result the return air temperature increases. By simply elevating the equipment heat density, the air management effectiveness improves.

Cases 1-3

For **Case 3**, there are less blanking panels, more floor leakage, and a lower supply temperature compared to Case 6. All changes are clearly visible in Figure 9. This combination, however, provides sufficient cooling of the upper parts of the racks by air *entering* through the mid-height gaps (empty shelves) in the racks.

There are as many floor “openings” in the hot aisles (floor leaks) as in the cold aisles (perforated tiles). Since the racks are pulling air from the cold aisle, the negative pressure will pull warmer air through the mid-height gaps from the rear of the racks, essentially re-using the floor leakage. This flow pattern has a significant effect on the need of supply air from the CRAC units. The 100/RTI is reduced from 1.86 to 1.40. Since this effect is a function of the vertical position of the gaps and the level of floor leakage in the hot aisles, it requires more scrutiny before these results can be generalized.

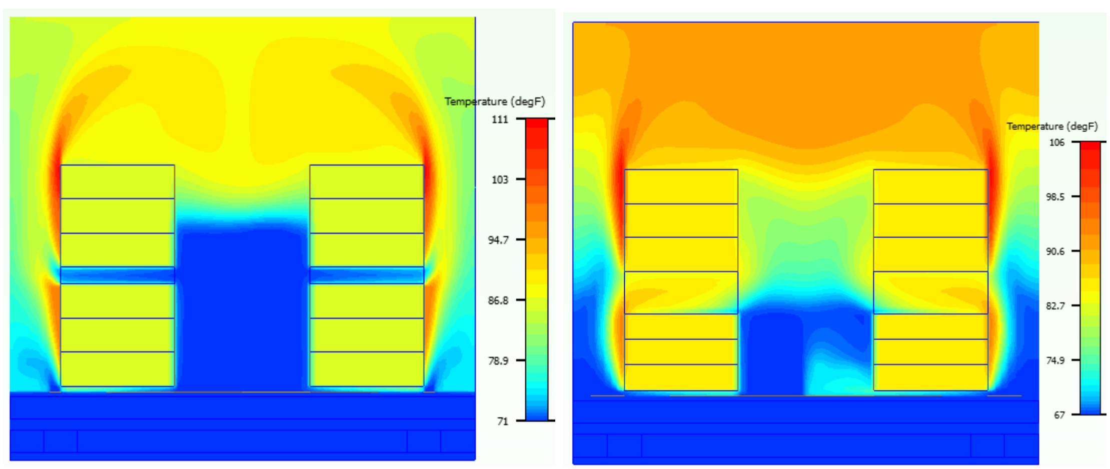

Figure 9: Temperature plots of Case 6 and Case 3. The cold air is leaving the cold aisle through the mid-height gaps in Case 6 but this airflow is reversed in Case 3.

The discontinuity in the temperature plot in Figure 10 is due to the inflow of warmer air through the mid-height gaps in the racks. The first curve segment represents cold air directly from the perforated tiles (lower shelves). The second curve segment represents a mixture of cold air from the perforated tiles and warm air coming through the mid-height gaps (upper shelves).

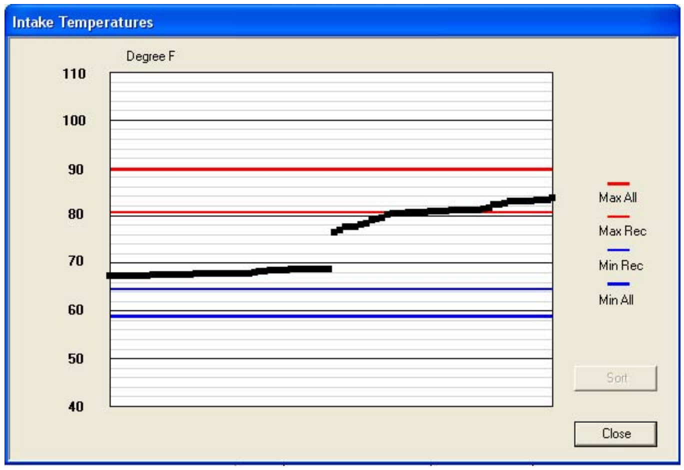

Figure 10: Plot of Intake Temperatures for Case 3
as drawn by the RCI™ Software (ANCIS 2010).

For **Case 2**, more "stray" tiles are added in the cross aisles just outside the cold aisles and the supply air temperature is dropped slightly (67° → 66°F) compared to Case 3. The added tiles benefit the end racks and the lower supply temperature benefits all racks. The two effects further reduce the supply air requirement from 1.40 to 1.30.

For **Case 1**, four racks are rotated 180° (simulating non-optimal EC Class equipment) and the supply temperature is dropped compared to Case 2. The effect of the lower temperature (63°F) is more important than the rotated racks. The airflow requirement is reduced to a low 1.14. There is only a marginal "spill-over" between racks; very little of the hot exhaust air from the rotated racks goes into the intakes of the neighboring racks. However, this result may change if the exhaust air leaves the equipment with a high velocity. As a sign of poor air management, the average rack intake air temperature is now 9.1°F higher than the supply air temperature.

Note again that Cases 4, 5, 9, and 13 are not included in this study.

6.4. Comparison with the DOE Air Management (AM) Tool

The correlation between the CFD modeling results and the current AM Tool depends on the level of air management, see yellow rows in Table 10.

For Cases 6, 7, 8, 10, and 11 (*relatively good* air management) the airflows determined in this study and the airflows calculated by the AM Tool show similar trends. But, the amount of supply air is generally higher for the modeled data. For Case 11 (full aisle enclosure), the results are identical. If the model verification in Section 7 does not contradict the study results, the quality of the AM Tool calculations could be improved by adopting the results from this study (that is, higher airflow rates).

Furthermore, the granularity of the AM Tool data could be improved by using a better interpolation algorithm between the data points in the look-up tables. This study has also highlighted the potential need to remove the controls component of the last grouping "Airflow Delivery" (see Section 4.2) in the look-up tables. All three measures will be considered for the next AM tool revision.

For Cases 1, 2, and 3 (*relatively poor* air management) the data sets diverge. The modeling results are discussed and explained above but there are not enough data to allow a generalization of the results. The required airflows in this study drop off with decreasing supply temperatures rather than increasing with poorer air management. As also discussed above, more study is warranted for these cases. Completing the excluded Cases 4 and 5 should provide some information. Another step would be to analyze the impact on the results when varying the vertical position of the gaps in the racks. No updates of the AM Tool are planned until data are available to support a generalization of the results.

Cases 12 and 14 do not have direct counterparts in the AM Tool, indicated by "N/A" in Table 10.

The last row in Table 10 shows the HVAC energy savings compared with Base Case 6 as calculated in this study. These calculations are based on a flow exponent of 2.8 to calculate fan energy savings from supply airflow rate and a factor of 2.0 (%/°F) to calculate chiller energy savings from supply temperature increase. Furthermore, based on data from LBNL benchmarking studies, it is assumed that 25% of the total HVAC energy is due to fan energy. The remaining 75% is due to chiller energy.

The effect on energy consumption due to changing supply temperatures is difficult to separate from that due to implementing air management measure. Temperatures and measures were often modified simultaneously, which complicate the analysis of Case 3 in particular. The fact that Cases 4 and 5 were not included in this study only increases these difficulties.

Nevertheless, maximizing blanking panels and minimizing floor leakage, especially with full cold-aisle containment (high segregation) provide the highest HVAC energy savings (22%) of the ten cases. Please note that the savings could be significantly larger if the reference case had been a system with Constant Air Volume (CAV) controls. The listed measures also allow high supply temperatures which make air-side economizers very effective (not included in percentage savings number above).

Again, Cases 1-3 need more study before the results can be generalized. By seemingly reducing the cold/hot air separation (Case 6 → Case 3), the energy usage actually improves by 8%. As it stands now, Base Case 6 has the least favorable energy performance. Finally, the study scope was too limited to allow a useful evaluation of the adequacy of the measure groupings used in the AM Tool.

Table 10: Comparison between data from this study and the DOE Air Management Tool. 100/RTI is the ratio between CRAC airflow and IT-equipment airflow.

Measures	Groupings of Quality Levels									
	#1	#2	#3	Base #6	#7	#8	#10	#11	#12	#14
1.Containment	1	1	1	1	2	2	2	3	1	1
2.Blanking panels	1	1	1	2	2	2	3	3	2	2
3.Floor leakage	1	1	1	2	2	2	3	3	2	2
4.Tile placement	1	1	2	2	2	3	3	3	2	2
5. EC-Class	1	3	3	3	3	3	3	3	3	3
6. Controls	3	3	3	3	3	3	3	3	CAV	3
7. AHU	2	2	2	2	2	2	2	2	2	2
8. Cable	2	2	2	2	2	2	2	2	2	2
SAT	63	66	67	71	71	72	74	74	71	71
100/RTI this study	1.14	1.30	1.40	1.86	1.70	1.72	1.45	1.20	1.86	1.47
100/RTI AM Tool	2.70	2.10	1.90	1.63	1.50	1.30	1.23	1.20	N/A	N/A
HVAC Energy	-7%	-8%	-8%	Ref	-6%	-7%	-17%	-22%	N/A	N/A

7. MODEL VERIFICATION

Introduction

The purpose of this section is to perform a preliminary verification of some of the Computational Fluid Dynamics (CFD) modeling results from Section 6 by comparing with data sets from the PG&E Air Management Incentive Program. Experiences from this exercise may lead to computer model, data center selection, and/or measurement refinements prior to any future research.

7.1 Data Set Selection

PG&E has implemented an air management incentive program for data centers. This program has generated a significant number of data sets. ANCIS reviewed and classified a total of 35 data centers from these data. The result can be viewed in the separately available spreadsheet "PG&E Data Set Compilation."

The compilation includes physical data center characteristics before air management changes as well as fan and chiller energy savings associated with the air management measures. The data was primarily compiled to help select data centers for this model verification. The following measures were implemented in the PG&E air management upgrades:

All data center:

- Install blanking panels in empty positions in racks
- Install strip curtains above racks and end of aisles.

Raised floor data centers:

- Remove perforated floor tiles from hot aisles
- Seal unintentional openings in raised floor.

Most data centers:

- Shut down CRAC units.

A few data centers:

- Install VFD on air handlers.

Not all 35 data sets could be used in the model verification since some data center characteristics had to be identical or near-identical to those assumed in the CFD modeling and the Air Management (AM) Tool. The three key characteristics were:

- Vertical Under-floor cooling (VUF)
- Hot and cold aisles
- Flooded return (no return plenum).

Only one data center had an exact match with these characteristics. The analysis was then expanded to include those data centers with *partial* hot/cold aisles. There were six data sets of this type. All-in-all, seven data sets or 20% of total were considered to have adequate characteristics.

7.2 Data Set Analysis

The data set analysis highlighted a few complications in the model verification effort. The data sets differ from the computer modeling in some important areas:

- The data for the data centers before air management measures were implemented often included substantial over-commissioning, whereas the computer modeling used "achievable" airflow.
- The fan systems were generally of the traditional Constant Air Volume (CAV) type with return air temperature sensing, whereas the computer modeling assumed ideal Variable Air Volume (VAV) control with intake temperature sensing.
- No standard was used for determining the thermal quality before and after the air-management measures were implemented, whereas the computer modeling used the Rack Cooling Index (RCI)™ to check for adequate thermal conditions.

These differences made an apple-to-apple comparison between the PG&E data and the model data challenging. For more reliable model verification, the coupling between the modeling data and the PG&E data needs to be tighter.

Since the CFD modeling focused on the supply airflows, the focus here will be on 100/RTI or the ratio of CRAC airflow to IT-equipment airflow. 100/RTI was calculated based on reported (initial conditions) or estimated by a PG&E algorithm (potential conditions) CRAC airflow, reported kW for the IT-equipment, and assumed temperature rise across the IT-equipment.

The first column in Table 11 shows 100/RTI for the initial conditions before air management measures were implemented. All listed data centers were initially equipped with CAV systems. The second column shows actual conditions after implementing air management measures, not including VAV. Thus, these data depend on the modularity of the air handlers. The third column lists potential or achievable conditions according to the PG&E algorithm using best-practice air management measures including VAV.

Only one of the seven data centers had actual data after air management measures had been implemented. As can be seen, the excess airflow (100/RTI) for Data Center A decreases by moving to the right in Table 11. One main reason the actual value is higher than the potential value is that CAV systems are less effective in matching the airflow with the demand compared to VAV systems.

There is a range of air management measures and other conditions among the seven data centers but the average values should be representative of those cases highlighted in Table 12. The un-weighted average values in Table 11 (highlighted in blue and green) will be used in the comparison with the CFD model data and the AM Tool.

Table 11: Summary of 100/RTI™ for the PG&E data. Cells highlighted in blue and green are used in the comparison with data in Table 12. 100/RTI is the ratio between CRAC airflow and IT-equipment airflow.

100/RTI	Before Measures (Initial Conditions) with CAV	After Measures	
		Actual with CAV	Potential with VAV
Data Center A	1.54	1.40	1.16
Data Center B	4.58	No data	1.66
Data Center C	3.01	No data	1.38
Data Center D	1.90	No data	1.11
Data Center E	3.44	No data	0.94
Data Center F	2.29	No data	1.01
Data Center G	2.29	No data	1.14
Average	**2.72**	**N/A**	**1.20**

In Table 12, the model values for Cases 1-3 (below average air management) are not included in this comparison due to the difficulties in generalizing these data per Section 6. The initial conditions fall within Cases #3-6 (average to below average conditions) whereas the potential conditions fall within Case #11. Please recall that Case #11 was defined as high quality of implementation of air management measures 1 through 6.

The average PG&E data for potential 100/RTI (1.20 in Table 11) determined by the PG&E algorithm is a perfect match with the CFD modeling and the AM Tool (see green highlights in Table 12). The fact that the same ratio was deduced based on three different methods provide good evidence that achieving much less than 20% over-ventilation is difficult.

Containing the equipment exhaust within the rack and providing a direct return path back to cooling units using a rack top duct and ceiling plenum return provides a precise separation of hot and cold air. Such a rack heat containment system (not included in the measures of the present study) with adequate controls may allow near perfect match between supply airflow and equipment airflow. However, avoiding overhead obstacles in the retrofit of an existing facility can be a challenge with these systems.

The average measured initial excess air (2.72 in Table 11) is consistent with the data in Table 12 (see blue highlight) when considering the fact that the PG&E data represent CAV systems and actual operating conditions whereas the model and AM Tool data represent ideal operation with VAV and intake sensing. CAV systems require more supply air than VAV systems since the modularity is never infinite. Another reason for over-ventilating data centers is to avoid hot spots. This analysis does not necessarily verify the model values but produce a check that they are reasonable.

Table 12: Summary results from CFD modeling and AM Tool. Cells highlighted in blue and green are used in the comparison with PG&E data in Table 11.

Measures	Groupings of Quality Levels									
	#1	#2	#3	Base #6	#7	#8	#10	#11	#12	#14
1.Containment	1	1	1	1	2	2	2	3	1	1
2.Blanking panels	1	1	1	2	2	2	3	3	2	2
3.Floor leakage	1	1	1	2	2	2	3	3	2	2
4.Tile placement	1	1	2	2	2	3	3	3	2	2
5. EC-Class	1	3	3	3	3	3	3	3	3	3
6. Controls	3	3	3	3	3	3	3	3	CAV	3
7. AHU	2	2	2	2	2	2	2	2	2	2
8. Cable	2	2	2	2	2	2	2	2	2	2
SAT	63	66	67	71	71	72	74	74	71	71
100/RTI this study	1.14	1.30	1.40	1.86	1.70	1.72	1.45	1.20	1.86	1.47
100/RTI AM Tool	2.70	2.10	1.90	1.63	1.50	1.30	1.23	1.20	N/A	N/A

7.3 Program Refinements

The model verification effort suggests some potential refinements to the PG&E Air Management Program. First, there is a need for improved and standardized documentation of the results, initial physical conditions, and which air management measures that were implemented. Second, since no standard was used to determine the thermal quality before and after the air-management measures were introduced, there is no way of knowing whether the thermal conditions were compromised. The Rack Cooling Index (RCI)™ could be utilized for this purpose in a similar fashion to the procedure outlined in Section 6.

8. CONCLUSIONS AND DISCUSSION

This section discusses key observations from this study. A well-designed and maintained air management system provides important benefits, including reduced operating costs (enhanced economizer utilization, higher chiller efficiency, and reduced fan energy), reduced capital investments (less HVAC equipment, and less real estate), cooling capacity regain (same mechanical equipment manages more load or less equipment manages same load), and enhanced equipment reliability (correct intake temperatures).

Air Management Data Review Report

The purpose of the Air Management Data Review Report is to review, analyze, and summarize some available data and research on air management in data centers.

- A number of case studies indicate high fan energy savings for certain measures such as equipment aisle enclosures with VFD supply fans. Fan savings in the 70-90% range and chiller savings in the 15-25% range are achievable (~35% savings on HVAC energy). The PG&E incentive program states fan savings in the range of 40-50%. The lower savings can be contributed to constant air volume (CAV) fans. Finally, the DOE Air Management (AM) Tool suggests typical fan energy savings of 60-80% and chiller energy savings of 15-20%.
- Despite readily available tools and performance metrics, there appears to be little to none similar research mapping potential energy savings from air management measures based on advanced computer modeling.

Modeling Results

Ensuring adequate IT-equipment intake temperatures can be accomplished by increasing the supply airflow and/or lowering the supply air temperature. In this study, however, the minimum airflow was determined at a fixed supply temperature. This is not the same as an optimization of supply airflow *and* supply temperature for the lowest energy use.

- The correlation between the CFD modeling and the current AM Tool depends on the quality of air management. For good air management, the modeled airflows and the calculated airflows show similar trends. However, the supply airflow is generally higher for the modeled data. The quality of the AM Tool would improve by adopting the results from this study. For poor air management the data sets diverge. This result is discussed and explained in the report but there are not enough data to allow a generalization. No updates of the AM Tool are planned until data are available to support a generalization.
- Maximizing blanking panels and minimizing floor leakage, especially with full cold-aisle containment provide the highest HVAC energy savings. Containment

allows higher supply temperatures which also make air-side economizers more effective. The savings would have been larger if the reference case had been a system with Constant Air Volume (CAV) fans.

- The modeling shows no change in required airflow with Constant Air Volume (CAV) fans compared to Variable Air Volume (VAV) fans. This implies that the airflow distribution was comparable. However, CAV fans cannot guarantee a match between the airflow delivered by the CRACs and the airflow ingested by the IT-equipment. In a CAV system, the airflow can only be reduced in discrete steps by turning CRAC units off. This procedure often results in a significant over-provisioning.
- Certain combinations of poor air management may prove more benign than generally thought due to reversal of airflow through rack openings, essentially re-using floor leakage. Such flow pattern significantly reduces the need for air from the CRAC units. Since it is difficult to know exactly what those combinations are (based on this study alone), well-organized hot and cold air separation is the best approach.
- At higher heat densities, the relative floor leakage is reduced since the number of perforated tiles is increased and the absolute floor leakage remains unchanged. The net effect is that the necessary excess airflow (data center over-ventilation) is reduced significantly and as a result the return air temperature increases. By simply elevating the equipment heat density, the air management effectiveness improves.
- Since IT-equipment protection is a top priority, energy efficiency measures must not negatively impact the thermal IT-equipment environment. Whatever thermal standard adopted, the effect of air-management measures on the environment should be checked. The Rack Cooling Index (RCI)™ was used for this purpose; one challenge with the PG&E data is that no such yardstick was used.

<u>Model Verification</u>

The purpose of the model verification was to perform a preliminary verification of some of the Computational Fluid Dynamics (CFD) modeling results by comparing with data from the PG&E Air Management Incentive Program. For more reliable model verification, the coupling between modeling data and PG&E data needs to be tighter.

- The PG&E calculated potential minimum over-ventilation of the data center is a perfect match with the CFD modeling and the AM Tool. The fact that the same supply airflow was deduced from three different methods provide good evidence that achieving much less than 20% over-ventilation is difficult.
- The PG&E measured initial over-ventilation (175%) is consistent with the CFD modeling and the AM Tool when considering that it represents CAV fans and CRAC return temperature sensing whereas the modeling and the Tool assume ideal operation with VAV fans and IT-equipment intake temperature sensing. CAV systems require more supply air than VAV systems since the modularity is not infinite. This analysis does not necessarily verify the model results but produce a check that they are reasonable.

9. RECOMMENDATIONS FOR FUTURE WORK

This report points to some areas where more research may be needed. The following are the main recommendations based on this study.

- To be able to generalize the results for poor air management, the selection of the empty equipment positions needs to be evaluated. The unexpected energy reduction compared with the base case is likely to deteriorate if the mid-height gaps are moved up (or down) and the floor leakage in the hot aisles is altered.
- This study is an exploratory effort rather than an optimization study. A well-crafted optimization study would determine the best combination of supply temperature and supply airflow for each of the modeling cases. However, this would be a significantly larger effort since two parameters are involved rather than just the supply airflow rate.
- For more reliable model verification, the coupling between the modeled and the measured data needs to be tighter. A controlled verification of the CFD modeling could be accomplished by developing a methodology for matching modeled conditions with measured conditions. CFD generally provide an accurate trend among the tested measures but not necessarily correct absolute values. Model verification is meant to assure that the level of accuracy is adequate.
- The model verification suggests some potential refinements to the PG&E Air Management Incentive Program. First, there is a need for improved and standardized documentation of the results, initial physical conditions, and which air management measures that were implemented. Second, since no standard was used to determine the thermal quality before and after the air-management measures were introduced, there is no way of knowing whether the thermal IT-equipment conditions were compromised.
- The study highlighted the need to make a number of refinements to the DOE Air Management Software Tool. Most importantly, it is recommended to adopt the results from this study for relatively good air management, remove the controls component of the Airflow Delivery group in the look-up tables, and introduce an interpolation algorithm for the data in the look-up tables.

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APPENDIX 1: Temperature Plots as Drawn by the RCI™ Software (ANCIS 2010)

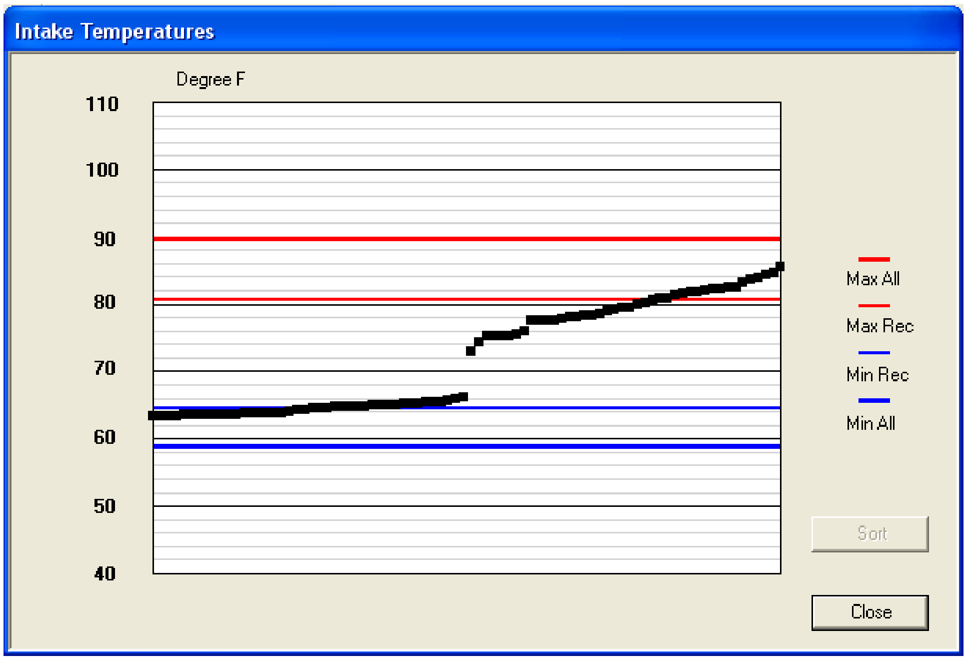

Figure A-1: Plot of Intake Temperatures for Case 1 (RCI=95%); SAT=63°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

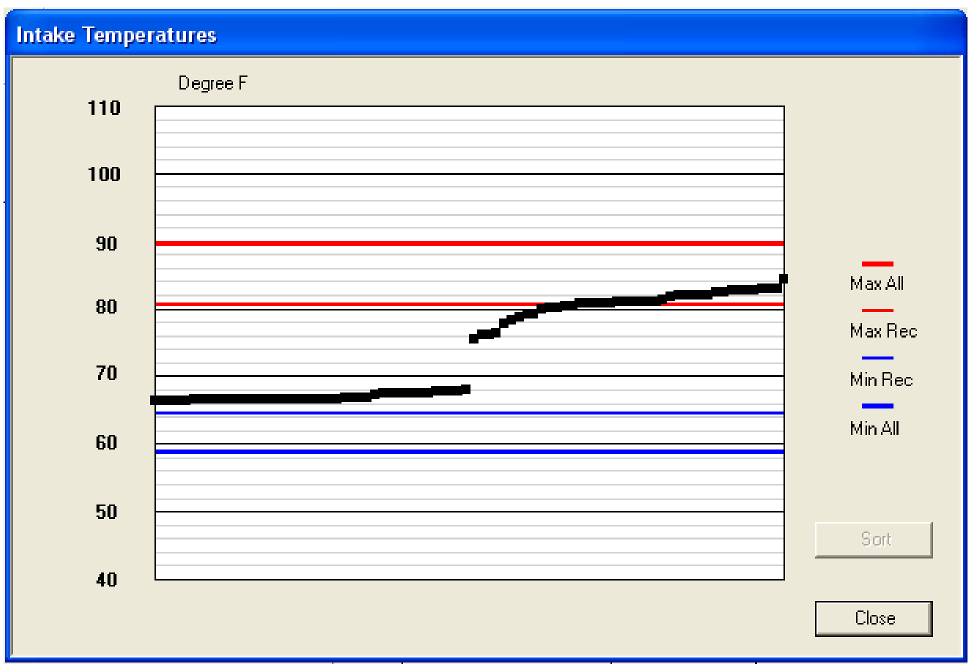

Figure A-2: Plot of Intake Temperatures for Case 2 (RCI=95%); SAT=66°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

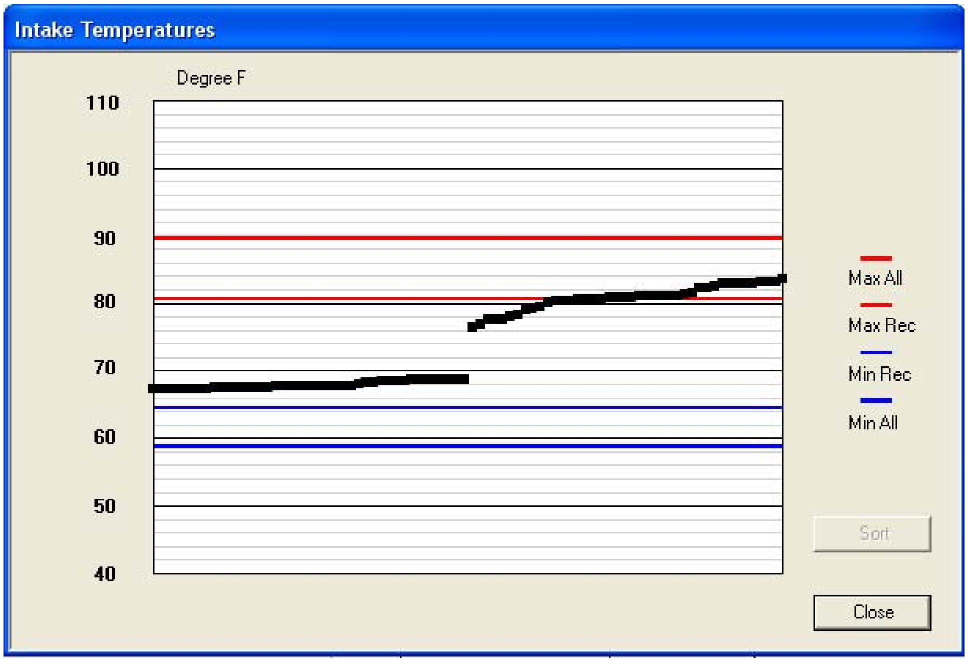

Figure A-3: Plot of Intake Temperatures for Case 3 (RCI=95%); SAT=67°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

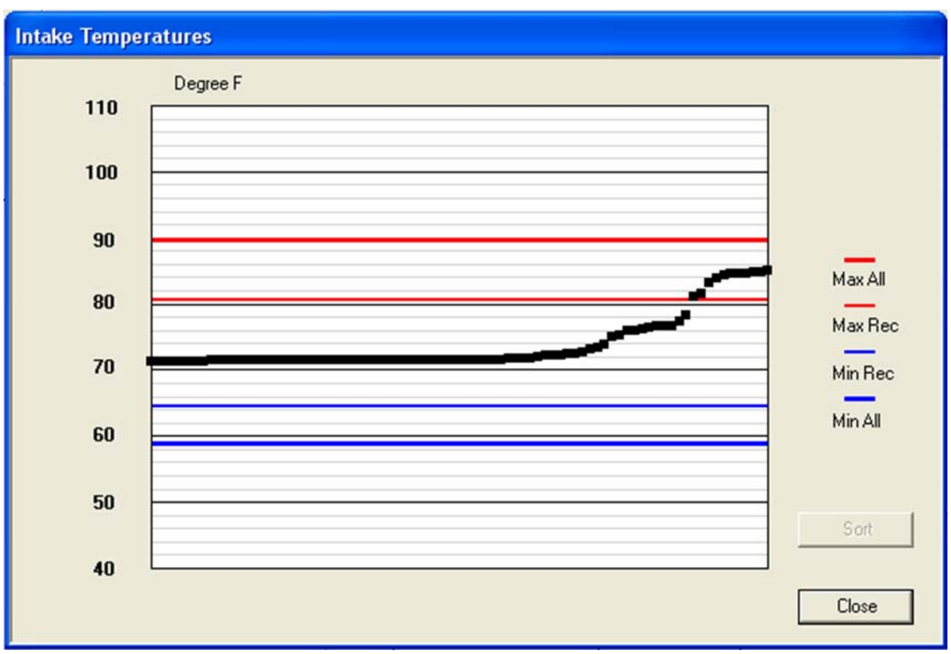

Figure A-4: Plot of Intake Temperatures for Case 6 (RCI=95%); SAT=71°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

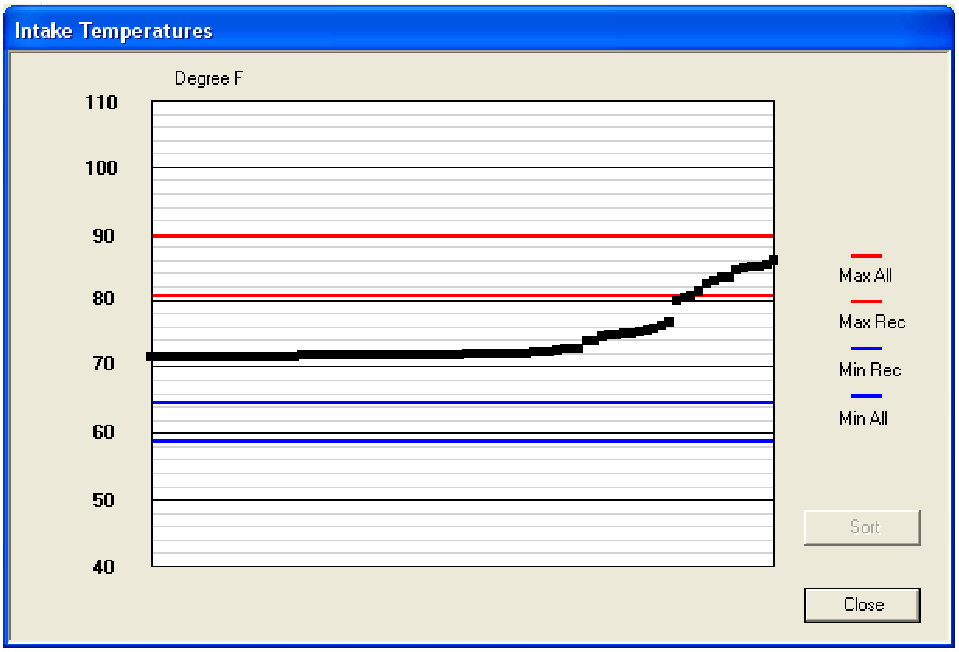

Figure A-5: Plot of Intake Temperatures for Case 7 (RCI=95%); SAT=71°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

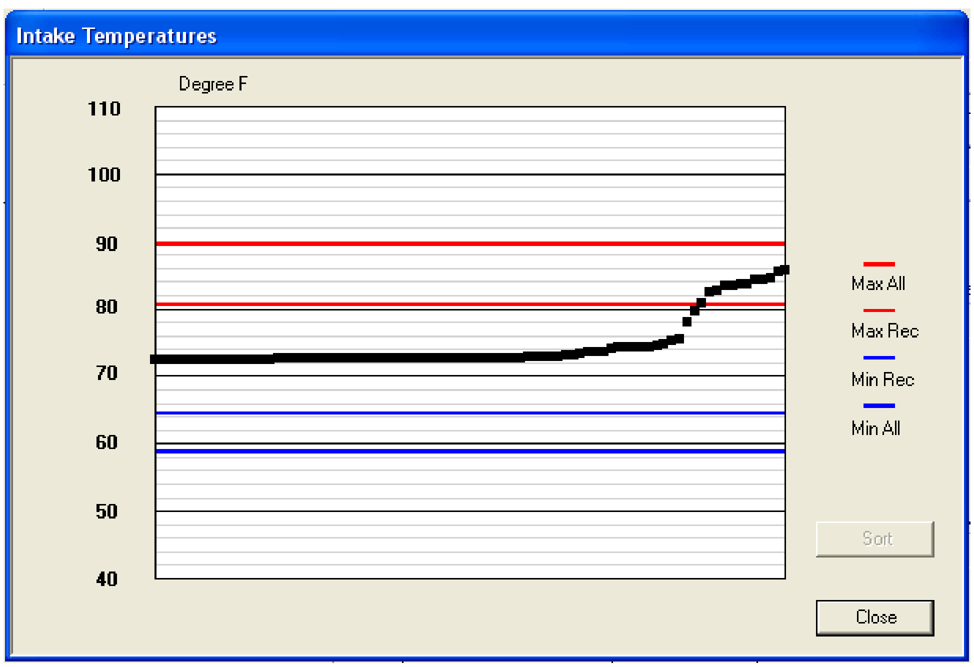

Figure A-6: Plot of Intake Temperatures for Case 8 (RCI=95%); SAT=72°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

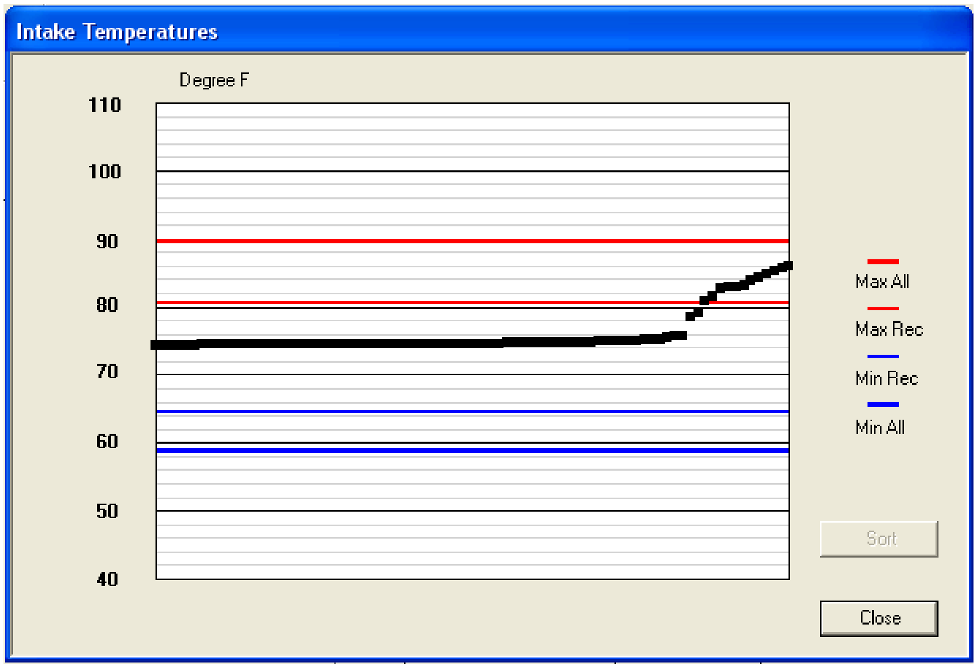

Figure A-7: Plot of Intake Temperatures for Case 10 (RCI=95%); SAT=74°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

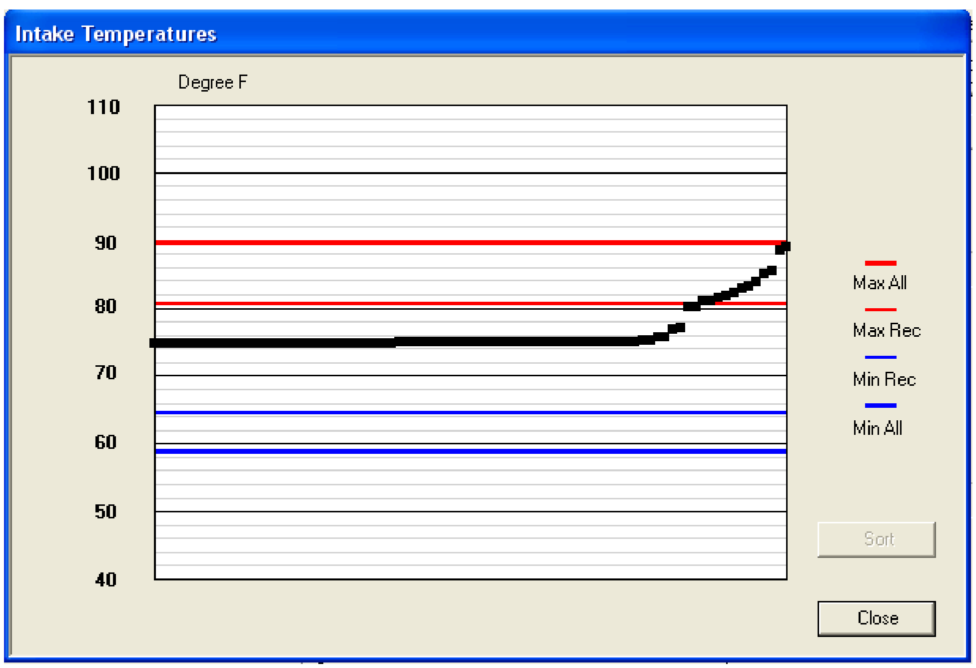

Figure A-8: Plot of Intake Temperatures for Case 11 (RCI=95%); SAT=74°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

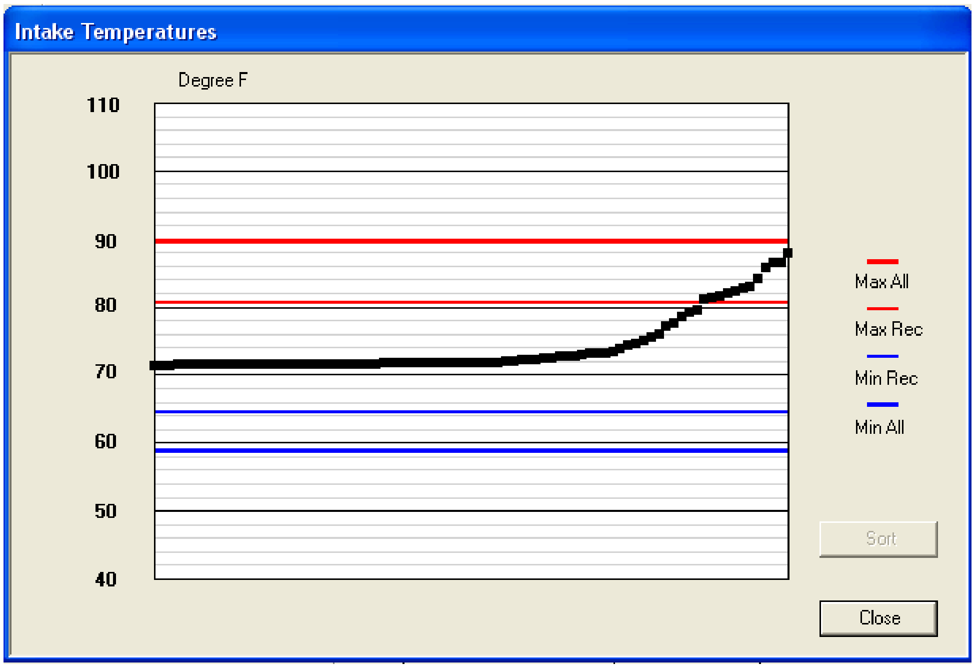

Figure A-9: Plot of Intake Temperatures for Case 12 (RCI=95%); SAT=71°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.

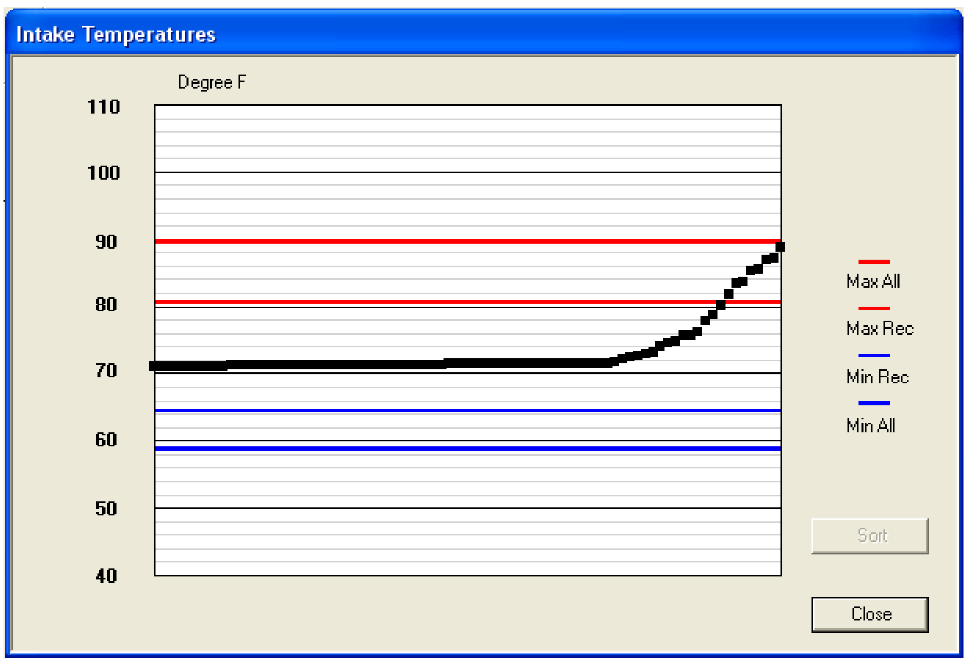

Figure A-10: Plot of Intake Temperatures for Case 14 (RCI=95%); SAT=71°F. The intakes have been arranged along the x-axis in order of increasing intake temperature.