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ENERGY-EFFICIENT AIR COOLING OF DATA CENTERS AT 2000 W/FT^2

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ABSTRACT
Increased Information and Communications Technology (ICT) capability and improved energy-efficiency of today's server platforms have created opportunities for the data center operator. However, these platforms also test the ability of many data center cooling systems. New design considerations are necessary to effectively cool high-density data centers. Challenges exist in both capital costs and operational costs in the thermal management of ICT equipment.

This paper details how air cooling can be used to address both challenges to provide a low Total Cost of Ownership (TCO) and a highly energy-efficient design at high heat densities. We consider trends in heat generation from servers and how the resulting densities can be effectively cooled. A number of key factors are reviewed and appropriate design considerations developed to air cool 2000 W/ft^2 (21,500 W/m^2). Although there are requirements for greater engineering, such data centers can be built with current technology, hardware, and best practices.

The density limitations are shown primarily from an airflow management and cooling system controls perspective. Computational Fluid Dynamics (CFD) modeling is discussed as a key part of the analysis allowing high-density designs to be successfully implemented. Well-engineered airflow management systems and control systems designed to minimize airflow by preventing mixing of cold and hot airflows allow high heat densities. Energy efficiency is gained by treating the whole equipment room as part of the airflow management strategy, making use of the extended environmental ranges now recommended and implementing air-side air economizers.

INTRODUCTION
New ICT systems often test the ability of many data center cooling systems. Effective design guidelines both boost the capacity of a particular data center and the energy efficiency. The purpose of this paper is to detail how air cooling can be used to provide a low TCO and a highly energy-efficient design at high heat densities by considering some fairly recent technology developments in data centers, both at the IT and infrastructure levels. Patterson [1] discussed how high density can provide a beneficial TCO. The present paper expands on that work by considering recent developments and looking at densities higher than covered there.

The densities discussed here needs to also be considered at the rack level. Currently, the highest density ICT equipment is found in blade servers. A fully populated rack of blades at their maximum density can reach 40kW rack power (or 2000 W/ft^2 with a rack density of one rack per 20 ft^2). The use of kW/rack provides greater insight into the specific rack-level cooling and power challenges. W/ft^2 can vary as the equipment layout and rack density affect the value greatly; W/ft^2 is a better metric for overall site capacity planning.

CONTRIBUTING FACTORS

The boost in cooling capacity and energy efficiency depends on a cascading effect of several contributing factors, including air-side economizers, relaxed environmental guidelines, improvements in temperature control strategies, Variable Air Volume (VAV) systems, enclosed equipment aisles, and higher ICT equipment temperature rise. These key factors are reviewed sequentially and appropriate design considerations developed.

Air –Side Economizers

The energy efficiency of air-cooled data centers is boosted by the wider acceptance of air-side economizers; a technology that has been successfully used in telecom centers for decades. With correct design and maintenance, savings are obtainable in most climates in the US and mechanical cooling can virtually be eliminated in some. When designed and maintained correctly, air quality can be maintained with minimal risk to the data center equipment. For example, some of the most sensitive facilities in existence, the semiconductor fabrication facilities, use very large amounts of outdoor air. The design of the economizer is imperative. It should allow blending of outdoor air and return air as well as allow partial chiller operation or the savings will be substantially reduced.

Relaxed Environmental Guidelines

The tight environmental controls as published by ASHRAE [2] have been replaced with wider environmental ranges. The updated ASHRAE Thermal Guidelines [3] has taken a step in that direction by increasing the recommended equipment intake temperature range to 65°-80°F (18°-27°C). This is now identical to the one specified by NEBS [4]. The result of operating at a higher temperature is more opportunities to save energy with or without air-side economizers. At these temperatures, the number of hours per year available for free cooling is greatly increased from the excessively cool supply temperatures that many data centers typically use. A survey by DatacenterDynamics [5] demonstrated the magnitude of over-cooling. 88% of the respondents were running below 75°F (24°C), with over 20% being below the minimum ASHRAE guideline of 65°F (18°C).

The wider range does not in and of itself allow higher density, but it does reduce the operating costs and should be part of any design for a new data center.

The ASHRAE guideline also changed the lower end on the humidity range, switching from a relative humidity (RH) guideline to one based on dew-point. The change has two benefits. The first is that the control of the cooling and humidification systems is much simpler with a dew-point limit. Second, the change lowered the humidity levels in much of the recommended temperature range, again adding to the number of hours per year where no additional treatment of the air is required.

The updated ASHRAE Thermal Guideline also addresses how to show compliance with the new temperature range. The Rack Cooling Index (RCI)™ is a performance metric [6] explicitly designed to gauge compliance with the thermal guidelines of ASHRAE (or any thermal guideline with recommended and allowable temperature ranges) for a given data center. This index compresses the intake temperatures to two numbers, RCI_{HI} and RCI_{LO}.

Over-temperatures exist once one or more intake temperatures exceed the maximum recommended temperature. Similarly, under-temperatures exist when intake temperatures drop below the minimum recommended. An RCI_{HI} of 100% means no over-temperatures whereas an RCI_{LO} of 100% mean no under-temperatures. Both numbers at 100% indicate that all temperatures are within the recommended temperature range, i.e., absolute compliance. The lower the percentage, the greater probability (risk) intake temperatures are above the maximum allowable and below the minimum allowable, respectively. Indication of such potentially harmful thermal conditions is provided by a warning flag "*" appended to the index. An index value below 90% is often characterized as poor.

Work by Herrlin, shown in Figure 1, proposes a chart for ICT-equipment air intake temperature compliance incorporating the RCI_{HI} and RCI_{LO} [7]. The thermal compliance should be checked whenever the data center design or operations is changed such that it may affect the thermal equipment environment.

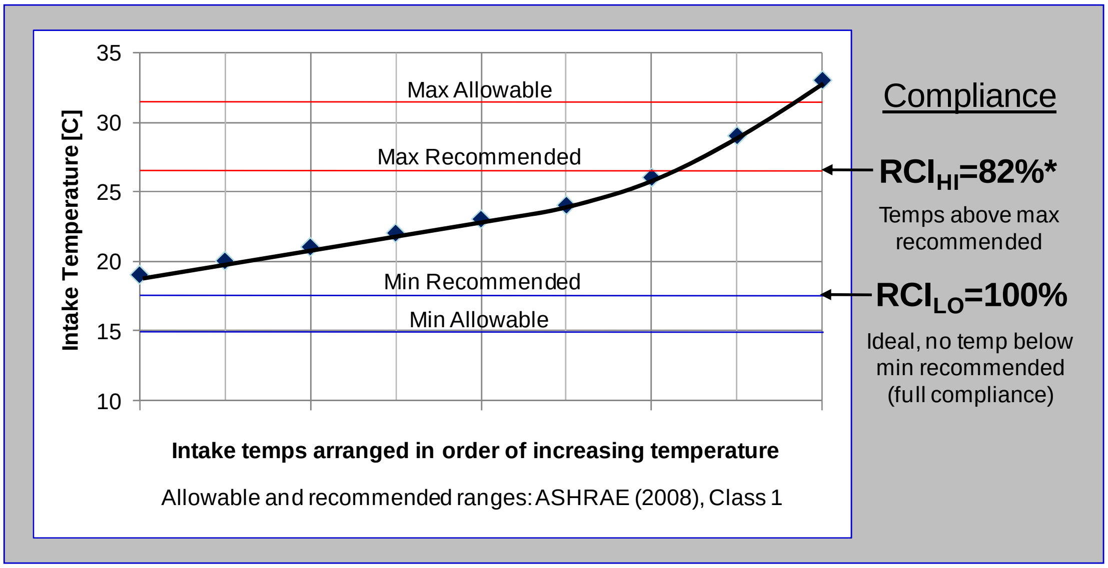

Figure 1: Proposed chart for ICT-equipment air intake temperature compliance by Herrlin [7].

Intake Temperature Control with VAV

Conventional control of cooling capacity is based on monitoring the return air temperature back to the air handler. However, the return temperature has little to do with the temperature that the air-cooled electronic equipment depends on for reliable operation. The norm has been to adjust the return temperature to control a few hot spots. This control method leads to costly overcooling of the rest of the data center.

Results from the Fall 2006 Liebert Data Center Users Group [8] meeting showed that of the respondents a full 76% were using thermostats in the return path to the Computer Room Air Conditioners (CRACs). To compound the less than optimum design, more than 92% of the respondents had set-points below 72°F (22°C). So not only are they measuring the temperature in a poor place, the CRAC *return* temperature is often cool enough to be supplied directly to the servers. Unfortunately these specific questions were not re-surveyed in latter years but it is the authors' beliefs that there has not been any significant change to these trends.

Today, intake or near intake temperatures can be used to control the cooling capacity by rearranging the perforated floor tiles and by utilizing VAV fans to ensure compliance with industry thermal guidelines. At least two energy benefits result; namely, increased supply air temperature (less chiller energy and better air-side economizer utilization) and reduced supply air volume (less fan energy). Correctly implemented, the end result is curtailed wasteful over-provisioning and improved equipment environment. Any adjustments of the supply temperature set-point or supply air volume control strategy should trigger a check of the thermal equipment environment, for example, by using the RCI.

Enclosed Equipment Aisles

An engineered airflow management system designed to minimize airflow by preventing mixing of cold and hot airflows is a prerequisite for allowing high heat densities. By utilizing enclosed equipment aisles, the inherent capacity of a raised-floor system may be increased substantially. One of the key limitations of raised-floor plenums is the poor pressure distribution at higher airflow rates. A poor pressure distribution means an unpredictable airflow through the individual perforated floor tiles or grates and variable airflow to the ICT equipment.

Figure 2 shows a high-density design of 380 W/ft^2 (4100 W/m^2) for an Intel data center based on CFD modeling performed by ANCIS. Two cold equipment aisles are shown with three rows of grates in each. Due to variations of raised-floor pressure, the airflow through the grates varied -62% to +45%. With a conventional open architecture, such variations lead to hot and cold spots. By incorporating air barriers to enclose the cold equipment aisles, however, the pressure distribution became a nonissue due to an effective averaging of the airflow rates through the grates located in each enclosed aisle. The RCI_{HI} and RCI_{LO} both improved to 100% (ideal).

Figure 3 was published by ASHRAE [9] to show the raised-floor capacity boost from deploying cold-aisle enclosures. Compared to an open architecture, the semi-enclosed architecture (doors to the cold aisles) improves the thermal conditions, that is, higher RCI_{HI} values. The fully enclosed design, however, provides a truly striking improvement of the thermal environment. Even at 30kW per rack, the RCI_{HI} is elevated to 100% (ideal). By utilizing fully enclosed cold aisles, the capacity of the raised floor was increased by an estimated two-three times.

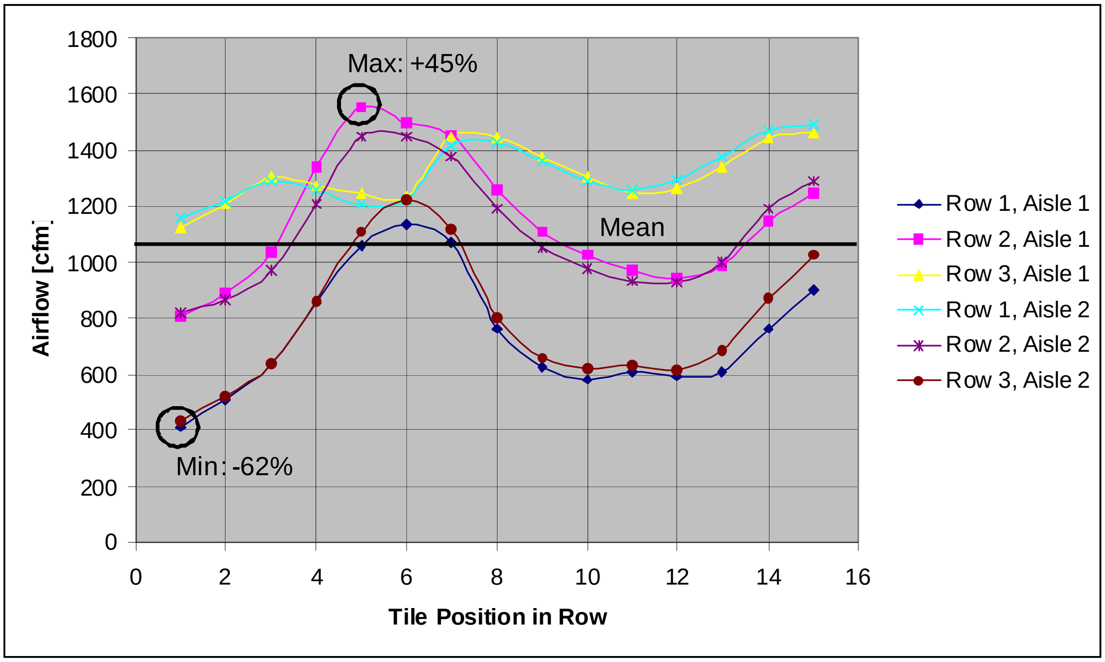

Figure 2: Inadequate grate airflow distribution due to poor raised-floor pressure.

The implications are great. Many data centers that are running out of capacity due to limited raised-floor heights can be reconfigured with cold-aisle enclosures to allow very significant heat densities. This should provide a welcome relief for many data center operators. The open and semi-enclosed architectures could be forced to RCI_{HI}=100% by increasing the supply airflow rate and accepting an energy penalty. At high densities, however, it is difficult to combat poor thermal conditions by increasing the supply airflow alone; a lower supply temperature is also generally required, further increasing the energy penalty.

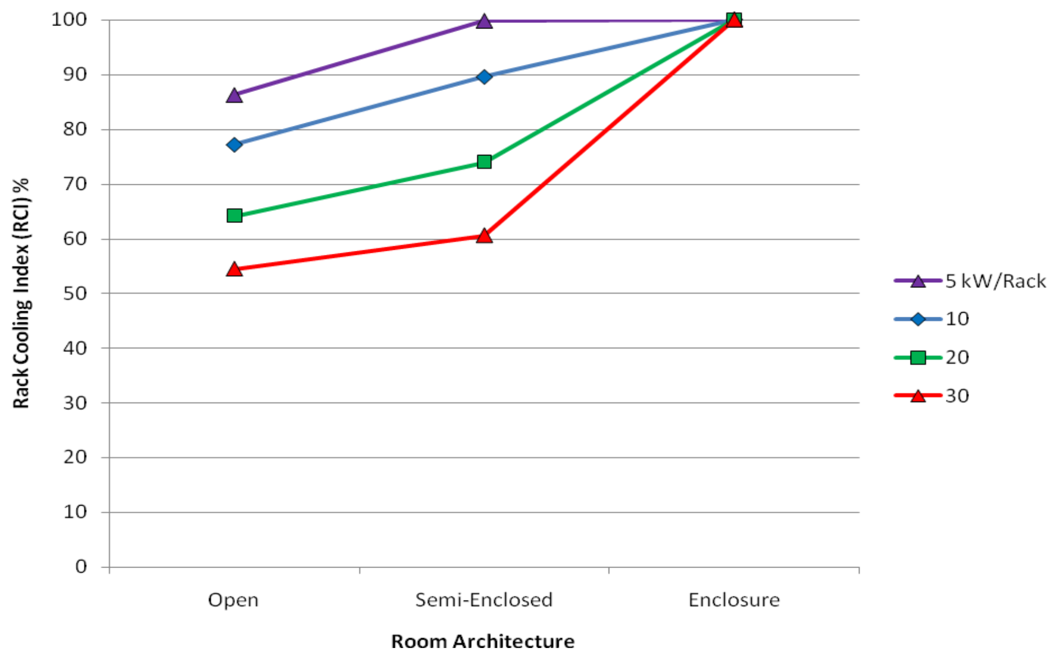

Figure 3: Thermal management improvement by cold-aisle containment as measured by RCI_{HI} [9].

The figure above was developed for a new supercomputer center by performing parametric runs with an established Computational Fluid Dynamics (CFD) model. Without such an advanced tool, this analysis would have been difficult to perform. CFD modeling is a key part of the analysis allowing high-density designs to be successfully designed and implemented.

Another less obvious implication of the enclosed hot or cold aisle is the benefit to reduce static pressure requirements of the cooling fan by using a more open floor tile. Typically 25% open tiles are used which can provide a reasonable airflow balance in the space. This balance is due to the high restrictive loss caused by the 25% open tile. If those tiles would be replaced with 56% open grates there would be a significantly less pressure drop across the floor tile. Initially this is a desirable result, however accompanying this is a much poorer airflow balance. With the more open tiles, the under floor layout and arrangement becomes a much greater impact on airflow resulting in a widely varying airflow tile to tile.

Only in the case of hot or cold aisle segregation does this imbalance not create significant issues and/or inefficiencies. In the segregation case, when properly controlled, the cold aisle becomes self balancing and can be largely unaffected by the different flows more prevalent in the more open tile designs. This advantage can then provide a significant energy use benefit requiring much less fan power to drive the air in the hot or cold aisle segregation strategy due to the more open tiles.

Higher Equipment Temperature Rise

As discussed above, improved cooling infrastructure allows radically higher heat densities in data centers. Another significant boost comes from the ITC equipment itself. New blade servers do not operate at the conventional 25°F (14°C) temperature rise but rather near twice that rise. The implications are again great. For the same heat load, only half of the air volume needs to be provided to cool the equipment. This will either double the cooling capacity of the raised floor cooling system or reduce the fan energy significantly (or a combination of the two). According to the fan laws, reducing airflow by ½ reduces fan energy by 87%.

The goal of the electronic equipment manufacturers is to maximize the temperature rise to limit the required airflow rate. This design change will reduce fan and fan-energy requirements as well as reduce the acoustical noise. For high-density racks as discussed in this paper (30-40kW per rack), there are significant design challenges to provide adequate cooling airflow rates at a reasonable noise level if they were operating at the conventional 25°F (14°C) temperature rise.

SUMMARY

This paper has outlined a compelling case for air cooling of high-density data centers from an energy and thermal management perspective. In addition, the demonstrated increase in cooling capacity of raised-floor systems has very positive economic benefits, not only for new high-density installations but for legacy, airflow-constrained, low density data centers as well. Owners of capacity strapped data centers may find that a new data center is not required to meet future expansion.

Key design factors were reviewed and appropriate design considerations developed to air-cool up to an estimated 40 kW rack or 2000 W/ft^2 (21,500 W/m^2). Although there are requirements for greater engineering, including Computational Fluid Dynamics (CFD) modeling, such data centers can be built with current technology, hardware, and best practices and yield very high efficiencies and the lowest TCO.

Energy efficiency is gained by treating the whole data center as part of the air-management strategy. The tight environmental guidelines of the past have been replaced with wider ranges, creating opportunities to save energy with or without air-side economizers. With the wider acceptance of economizers, savings are obtainable in most climates and mechanical cooling can virtually be eliminated in some. In addition, the implications with higher ICT-equipment temperature rise are great. The customary temperature rise across modern blade servers will increase the cooling capacity of the raised floor and reduce fan energy costs.

The typical data center design with open aisle architecture and the return air conditions controlling the cooling system severely limit the heat density and energy efficiency. A well-engineered air-management systems and a control system designed to minimize airflow by preventing mixing of cold and hot airflows allow high heat densities. By utilizing enclosed equipment aisles in conjunction with raised-floor systems, the inherent capacity of the floor can meet the required airflows of fully loaded ICT racks. Finally, equipment intake temperature control of VAV air handlers in conjunction with rack inlet temperature compliance metrics provides great energy and thermal management benefits.

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