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Airflow and Cooling Performance of Data Centers: Two Performance Metrics

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ABSTRACT

This paper focuses on the use of performance metrics for analyzing air-management systems in data centers. Such systems are important for adequately cooling the electronic equipment and controlling the associated energy costs. Computational Fluid Dynamics (CFD) modeling has the capacity to help understand how a cooling solution will perform prior to being built. However, modeling also has the capacity to generate an unwieldy amount of data. The crux of the matter is to know what to look for and then objectively characterize and report the performance.

Performance metrics provide a great opportunity for the data center industry at large. They could form the foundation for a standardized way of specifying and reporting various cooling solutions. This paper specifically demonstrates the use of two metrics: The Rack Cooling Index (RCI) is a measure of how well the system cools the electronics within the manufacturers' specifications, and the Return Temperature Index (RTI) is a measure of the energy performance of the air-management system. Combined, they provide an opportunity to judge the performance of the air-management system in an objective way subsequent to comprehensive CFD modeling.

A real-world example is given for demonstrating the use of these metrics to design a high-density data center. The analysis was designed to answer whether a fairly conventional raised-floor system could support significantly higher heat densities than was previously thought. By enclosing the cold equipment aisles, it is demonstrated that the cooling capacity can indeed be greatly increased. This should provide a welcome relief for many data centers that are currently running out of capacity due to a low raised floor.

INTRODUCTION

The main task for a data center facility is to provide an adequate equipment environment, and a relevant metric for equipment intake temperatures should be used to gauge the thermal environment. The Rack Cooling Index (RCI) is a measure of how effectively equipment racks are cooled and maintained within industry temperature guidelines and standards (Herrlin 2005). The Index is designed to help evaluate the equipment room "health" for managing existing environments or designing new ones. It is also well suited as a design specification for new data centers.

Herrlin and Belady (2006) demonstrated the use of the RCI for evaluating overhead and under-floor air distribution in data centers. There has been a continued interest in understanding the behavior of various cooling technologies in data centers. One issue is whether gravity plays a role in high-density environments with open room architectures. CFD modeling in conjunction with the Rack Cooling Index (RCI) was used to demonstrate that gravity-assisted air mixing is indeed central to creating an adequate and "forgiving" thermal equipment environment.

The Return Temperature Index (RTI) was introduced by Herrlin (2007) as a measure of the level of by-pass air or recirculation air in the equipment room. Both effects are detrimental to the overall thermal and energy performance of the space. By-pass air does not participate in cooling the electronic equipment and depresses the return air temperature. Recirculation, on the other hand, is one of the main reasons for hot spots or areas significantly hotter than the average space temperature.

Since the costs/savings associated with improving the RCI needs to be known, the concept of cost functions was

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developed based on costs to condition the equipment space (Herrlin and Khankari, 2008). By combining the Rack Cooling Index (RCI) with cost functions, current or planned equipment room designs can be better evaluated. Combining the RCI with cost functions provides comprehensive design information for the data center owner and/or consultant.

The present paper takes the analysis one step further. Given that air distribution from a raised floor is by far the most common way of cooling data centers, this air-distribution scheme is used to demonstrate the usage of the RCI combined with the RTI. Both metrics are computed with Computational Fluid Dynamics (CFD) modeling to evaluate the thermal equipment environment for different heat densities and room architectures for a fixed raised-floor height.

Others have suggested related metrics; for example, the Supply Heat Index (SHI) and the Return Heat Index (RHI) (Sharma, et al, 2002). These two dimensionless indices not only provide a tool to understand convective heat transfer in the equipment room but also suggest means to improve the energy efficiency. VanGilder and Shrivastava (2007) introduced the dimensionless Capture Index (CI), which is a cooling performance metric at the equipment rack level. The CI is also typically computed by CFD modeling.

Finally, although all stakeholders would benefit from using performance metrics such as the RCI and RTI, the data center owner and/or operator would maybe benefit the most. There is now the opportunity for them to specify a certain level of performance of the air-management system. The designer or contractor would also be able to demonstrate the performance of different design permutations and the final design. And, the cooling equipment manufacturers have another tool to refine their products.

DESIGN OF DATA CENTER

The design of a high-density data center is used to demonstrate the benefits of using the RCI and RTI. A number of CFD simulations were performed to quantify the possibility to substantially enhance the performance of a fairly conventional four-foot raised floor design for a new supercomputer center facility. It was desirable to avoid a two-story design that sometimes is used for extreme heat densities.

The comparison involves four heat densities (5kW, 10kW, 20kW, and 30kW per rack) and three room architectures (open, semi-enclosed, and enclosed). The highest density corresponds to more than 1000W/ft^2. The open or traditional architecture does not use physical barriers to enhance the separation of hot and cold air in the equipment room. The semi-enclosed architecture uses doors at the end of the equipment rows to help contain the cold air in the cold aisles and avoid detrimental air mixing. Finally, the enclosed architecture separates the cold aisle from the rest of the equipment room by barriers that enclose the entire aisle. Air mixing can thereby be kept to a minimum.

Figure 1 shows isometric views of the three room architectures and corresponding temperature maps of the intake temperatures of one lineup as computed by CFD modeling. This limited sub-domain was selected for the parametric analysis; the rest of the equipment space is a repetition of these two lineups.

The 10,000 ft^2 data center is cooled by air-handlers that provide the required airflow into the raised-floor plenum from galleries outside the room. The supply temperature is 65°F, and the supply airflow is 100% of the total rack airflow (the volume that the electronic equipment draws). Perforated floor tiles (grates) deliver the air from the raised-floor plenum into the cold aisles in front of the electronic equipment.

It can be seen from the temperature maps that the aisle doors limit the outflow of cold air into the equipment room whereas the enclosure essentially isolates the cold aisle. The characteristic wave form of cold air seen in the first two architectures is due to poor pressure distribution in the floor plenum and—in turn—poor airflow distribution through the perforated floor tiles. The result is significantly elevated intake temperatures at the bottom of the wave.

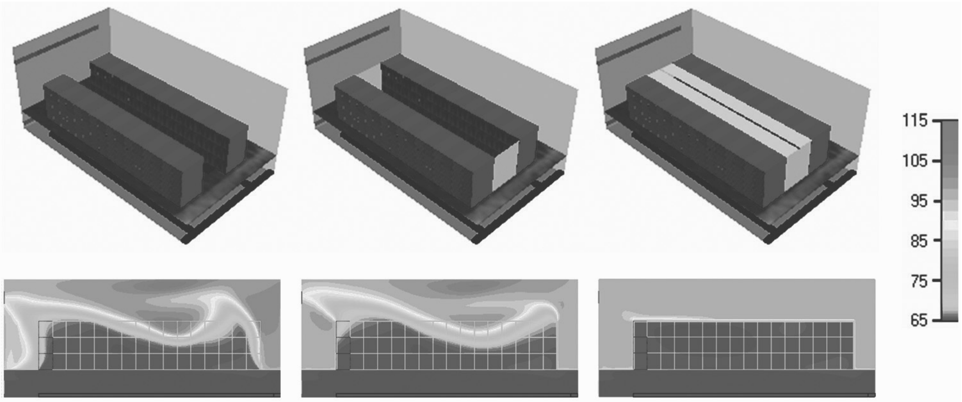

Figure 1 *Comparison of three room architectures (open, semi-enclosed, and enclosed) and corresponding intake temperature maps along one equipment lineup at 20 kW/rack.*

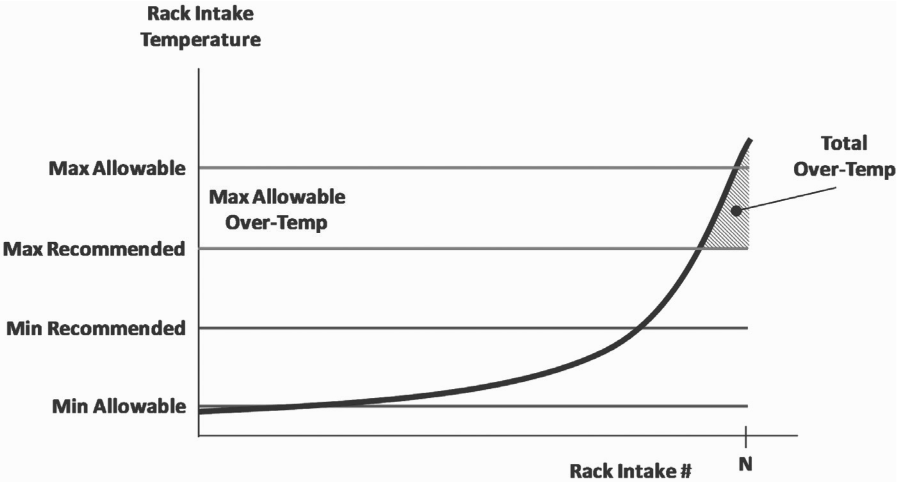

Figure 2 *Hypothetical intake temperature distribution and graphical representation of the* RCI_{HI}.

Almost every air-management design process includes analyzing permutations to arrive at the final design, including that of designing the supercomputer center. But how can the permutations readily be communicated to provide the foundation for finding the optimal design? One of the strong features of CFD modeling is also one of the weak ones; namely, the wealth of available output. The RCI and RTI metrics were deployed in this particular effort to condense the output. The rationale and definition of these metrics are described below.

Crafting a metric is a delicate balance between simplicity and accuracy. There is always a temptation to make an index too complicated to capture "everything." That approach generally defeats the purpose. Effective metrics often are strikingly simple.

RACK COOLING INDEX (RCI)^{TM}

The following is a brief overview of the Rack Cooling Index (RCI) to provide the necessary understanding how to interpret the index. For a complete description of the RCI, the reader is referred to the original work by Herrlin (2005) as published by ASHRAE.

The index deals with rack intake temperatures—the conditions that air-cooled equipment depend on for its continuous operation. The allowable intake temperature limits in Figure 2 represent the equipment design conditions whereas the recommended limits refer to preferred facility operation. Over-temperature conditions exist once one or more intake temperatures exceed the maximum recommended temperature. The total over-temperature represents a summation of over-temperatures across all rack inlets. Similarly, under-temperature conditions exist when intake temperatures drop below the minimum recommended. The numerical values of these limits depend on the applied guideline (e.g., ASHRAE 2004) or standard (e.g., Telcordia 2001, 2002).

Compliance with a given intake temperature specification is the ultimate cooling performance metric; the RCI is such a metric. RCI=100% mean ideal conditions; no over- or under-temperatures, all temperatures are within the recommended temperature range.

Table 1. Rating of the RCI

Rating	RCI
Ideal	100%
Good	≥96%
Acceptable	91-95%
Poor	≤90%

ASHRAE (2004) "Class 1" data center environment is used for the RCI calculations in this example. In the ASHRAE specification, the recommended equipment intake temperature range is 68°–77°F (20°–25°C) and the allowable range is 59°–90°F (15°–32°C). Table 1 shows an approximate rating of the RCI based on numerous analyses.

The RCI has two parts, describing the equipment room health at the high (HI) end and at the low (LO) end of the temperature range, respectively. Figure 2 provides a graphical representation of the RCI_{HI}. An analogous Index is defined for temperature conditions at the low end of the temperature range, RCI_{LO}.

The RCI_{HI} definition is as follows:

$$RCI_{HI} = \left[1 - \frac{\text{Total Over-Temp}}{\text{Max Allowable Over-Temp}}\right] 100 \; [\%] \qquad (1)$$

The hands-on interpretation of the Index is as follows:

$RCI_{HI} = 100\%$
All intake temperatures ≤ max recommended temperature

$RCI_{HI} < 100\%$
At least one intake temperature > max recommended temperature

$$RCI_{HI} < 0\%$$

At least one intake temperature > max allowable temperature

The RCI_{HI} is a measure of the absence of over-temperatures; 100% means that no over-temperatures exist (ideal). The lower the percentage, the greater probability (risk) that equipment experiences temperatures above the maximum allowable temperature. A warning flag "*" appended to the index indicates that one or several intake temperatures are outside the allowable range. The index for the hypothetical intake temperature distribution shown in Figure 2 is approximately $RCI_{HI} = 95\%$*.

CFD modeling provides a convenient tool for computing all intake temperatures that are necessary for calculating the index. Based on such modeling, Figure 3 shows the example results as measured by the RCI_{HI}. Presenting the results in this compact format provides an opportunity to detect trends that otherwise might have been lost in the large data stream. Every designer has a "metric" in mind whenever he/she is judging whether a design is adequate. The challenge of such unwritten metrics is that there are probably as many metrics as there are designers. The RCI, on the other hand, provides and unbiased and objective way of quantifying the quality of an air management design from a thermal perspective.

Compared to the open traditional architecture, the semi-enclosed architecture improves the thermal conditions, that is, higher RCI_{HI}. The enclosed design, however, provides a truly striking boost to the cooling capacity of the raised floor. Even at the 30kW per rack level, the RCI_{HI} is elevated to 100% (ideal). 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 centers. Finally, it should be noted that the enclosed architecture may be more vulnerable to catastrophic cooling outages, and engineered thermal solutions are often required to safeguard the servers.

RETURN TEMPERATURE INDEX (RTI)^{TM}

In the case of the open or semi-enclosed architecture, the RCI_{HI} can be improved by increasing the supply airflow rate and/or lowering the supply air temperature. However, these measures are associated with an energy penalty. The Return Temperature Index (RTI) is a measure of the energy performance of the air-management system. Deviations from 100% are an indication of declining performance. The index is defined as follows (Herrlin, 2007):

$$RTI = [(T_{Return} - T_{Supply}) / \Delta T_{Equip}]\ 100\ [\%] \tag{2}$$

where

T_{Return} = return air temperature (weighted average)

T_{Supply} = supply air temperature (weighted average)

ΔT_{Equip} = temperature rise across the electronic equipment (weighted average)

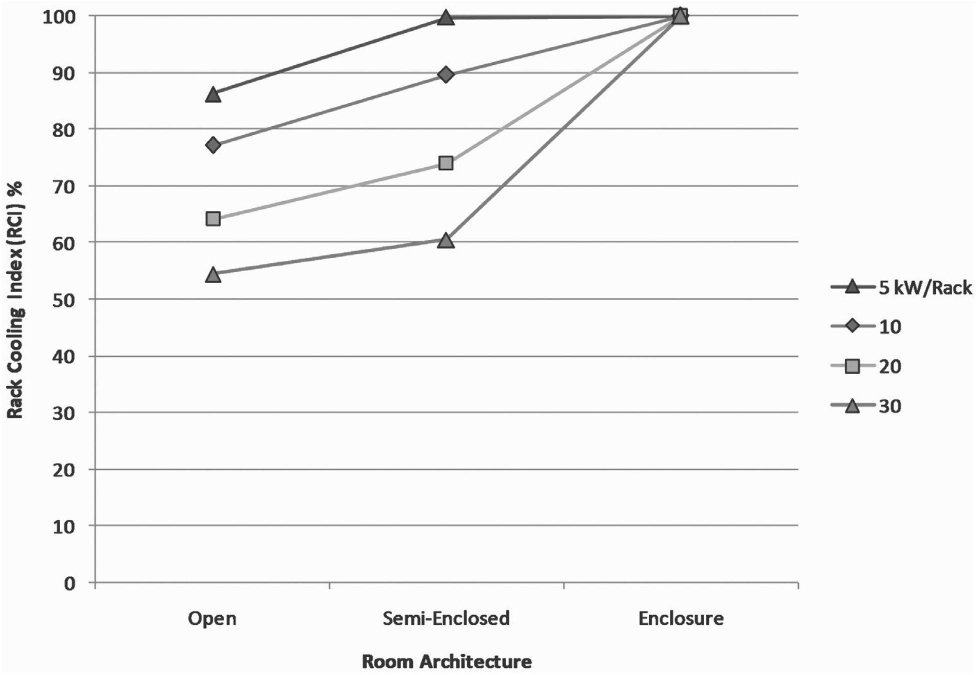

Figure 3 *RCI_{HI} as a function of heat density and room architecture (connecting straight lines are not necessarily a physical representation).*

Since the temperature rise across the electronic equipment provides the potential for high return temperatures, it makes sense to normalize the RTI with regard to this entity. In other words, the RTI provides a measure of the actual utilization of the available temperature differential. Consequently, a low return air temperature is not necessarily a sign of poor air management. If the electronic equipment only provides a modest temperature rise, the return air temperature cannot be expected to be high. Many legacy servers and other electronic systems have a temperature rise of only 10°F whereas new blade servers can have a temperature differential of 50°F.

The interpretation of the index is straight forward (Table 2): Deviations from 100% are an indication of declining performance. A number above 100% (over-utilization) suggests mainly air recirculation, which elevates the return air temperature. Unfortunately, this also means elevated equipment intake temperatures and poor RCI values. A number below 100% (under-utilization) suggests mainly air by-pass; cold air by-passes the electronic equipment and is returned directly to the air handler, reducing the return temperature and the energy performance. This often happens when the supply flow is increased to combat hotspots.

Table 2. Rating of the RTI

Rating	RTI
Target	100%
Recirculation	>100%
By-Pass	<100%

Note that there might be a number of legitimate reasons to operate below or above 100%. For example, some air-distribution schemes are designed to provide a certain level of air mixing (recirculation) to provide an even equipment intake temperature. Some overhead air-distribution systems operate this way.

Finally, Figure 4 shows the air-management and energy penalty as expressed by the RTI of taking the 5 and 10 kW racks to an RCI_{HI} of 100% by increasing the supply airflow rate. At higher densities, it is difficult to combat poor RCI values by increasing the supply airflow rate alone; a lower supply temperature is also generally required. As expected, the RTI (i.e., the energy performance) declines from 100% for the open and semi-enclosed architectures; the reduction is inversely proportional to the necessary increase in airflow. Since the RTI is below 100%, some air by-passes the electronic equipment. This demonstrates that an RCI analysis should be accompanied by an energy analysis; in this case by using the RTI.

Once again, the RCI and RTI metrics provide yardsticks for ranking design permutations. Each user, however, needs to determine the proper balance between the rack cooling effectiveness, energy performance, and other considerations.

DISCUSSION

This paper describes two performance metrics for analyzing air-management systems in data centers. Given that air-distribution from a raised floor is the most common way of cooling data centers, this scheme was used to demonstrate the use and benefits of the metrics. The Rack Cooling Index (RCI) was computed with Computational Fluid Dynamics (CFD) modeling to evaluate the thermal equipment environment in a

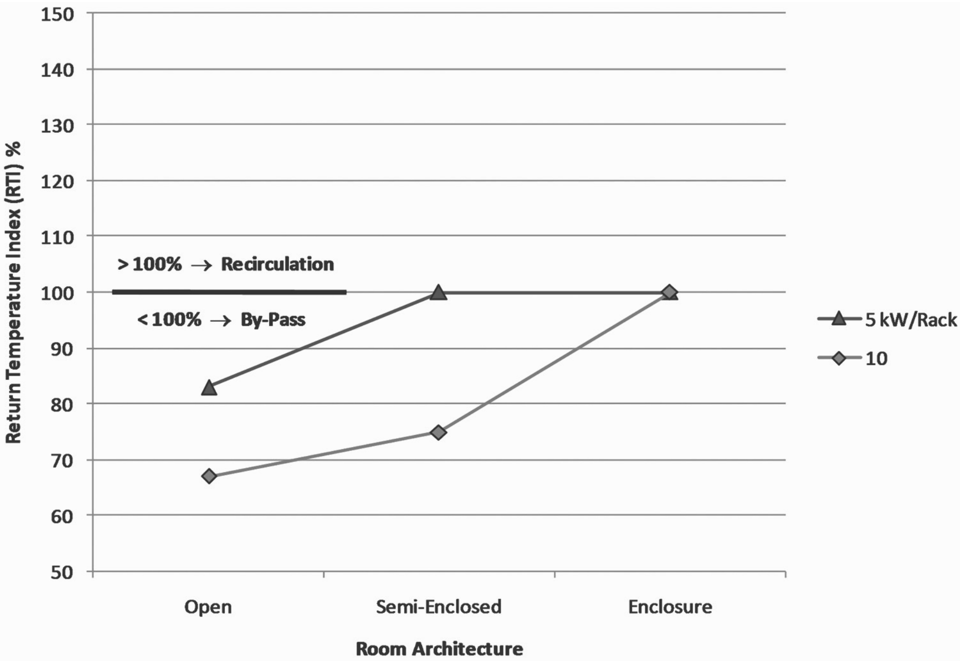

Figure 4 *Deterioration of the RTI and the energy performance by taking the* RCI_{HI} *to 100% (by "lifting" the 5 and 10 kW line in Figure 3 to* $RCI_{HI} = 100\%$*).*

new supercomputer center at four different heat densities and three room architectures. The RCI is a measure of how effectively equipment racks are cooled and maintained within a given temperature specification.

By utilizing the RCI, it was shown how the cooling capacity of the raised-floor system can be significantly boosted by enclosing the cold equipment aisles. The capacity limitation with raised floors has to do with a poor pressure distribution in the floor plenum at high air velocities; poor pressure distribution leads to poor airflow distribution through the perforated floor tiles. By enclosing the cold aisles, however, the airflow distribution becomes less important and the airflow can be increased to levels that would have been prohibitively high in conventional open room architectures. However, it is imperative that the floor plenum is both designed and maintained for accommodating high airflow rates.

The Return Temperature Index (RTI) provided information for improving the conventional open room architecture by increasing the airflows. The RTI is a measure of the performance of the air-management system and how well it controls by-pass air or recirculation air. Since improving the RCI_{HI} can lead to an energy penalty, the RTI can help evaluate how severe such a penalty may be. Indeed, it was demonstrated that the RTI was significantly reduced by bringing the RCI into absolute compliance (RCI_{HI}=100%).

Advanced Computational Fluid Dynamics (CFD) modeling applied to data center analysis can be enhanced by using metrics such as those outlined in this paper. The data center designer not only needs advanced analytical tools but he/she needs practical tools to make more informed decisions. Well crafted metrics will undoubtedly play an important role.

REFERENCES

ASHRAE. 2004. Special Publication, Thermal Guidelines for Data Processing Environments. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Herrlin, M. K. and Khankari, K. 2008. Method for optimizing equipment cooling effectiveness and HVAC cooling costs in telecom and data centers. ASHRAE Transactions, Volume 114, Part 1, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Herrlin, M. K. 2007. Improved Data Center Energy Efficiency and Thermal Performance by Advanced Airflow Analysis. Digital Power Forum, 2007. San Francisco, CA, September 10-12, 2007.

Herrlin, M. K. and Belady, C. 2006. Gravity-Assisted Air Mixing in Data Centers and How it Affects the Rack Cooling Effectiveness. ITherm 2006, San Diego, CA, May 30–June 2, 2006.

Herrlin, M. K. 2005. Rack Cooling Effectiveness in Data Centers and Telecom Central Offices: The Rack Cooling Index (RCI). ASHRAE Transactions, Volume 111, Part 2, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Sharma, R. K., C. E. Bash, and C. D. Patel. 2002. Dimensionless Parameters for Evaluation of Thermal Design and Performance of Large-Scale Data Centers. American Institute of Aeronautics and Astronautics, AIAA-2002-3091.

Telcordia. 2002. Generic Requirements NEBS GR-63-CORE, NEBS Requirements: Physical Protection, Issue 2, April 2002, Telcordia Technologies, Inc., Piscataway, NJ.

Telcordia. 2001. Generic Requirements NEBS GR-3028-CORE, Thermal Management in Telecommunications Central Offices, Issue 1, December 2001, Telcordia Technologies, Inc., Piscataway, NJ.

VanGilder, J.W. and Shrivastava, S.K. 2007. Capture Index: An Airflow-Based Rack Cooling Performance Metric. ASHRAE Transactions, Vol. 113, Part 1, pp.126-136. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

DISCUSSION

Mike Scofield, President, CMS Co., Sebastopol, CA: What is the recommended cold-aisle relative humidity, and why?

Magnus K. Herrlin: My presentation did not touch on relative humidity but rather dry-bulb temperature. Generally speaking, however, the acceptable equipment intake relative humidity range depends on the application. Too high humidity may lead to hygroscopic dust failures and too low humidity may lead to electrostatic discharge failures.