A data center in Utah uses waste heat from the IT equipment for space humidification in the winter; evaporative cooling in summer; reduced primary airflow to the IT equipment; strategic hot air recirculation; and novel controls that enabled the data center to achieve very high cooling efficiency at reduced first cost.

HONORABLE MENTION
INDUSTRIAL FACILITIES, NEW

Free Cooling for Data Center

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Six years ago, using outdoor air in cold climates for data enters was limited. Although free cooling from outdoor cold air, or air-side economization, is as old as civilization, data centers have been reluctant to adopt this technology. This may be because outdoor cold air is naturally dry, and when it picks up heat in data center spaces, its relative humidity drops to levels where humidification is needed to protect the IT equipment from static electricity.

Though some advocate maintaining a much lower level of indoor humidity in data centers, which would reduce need for humidification (ASHRAE TC 9.9, *Mission Critical Facilities, Data Centers, Technology Spaces and Electronic Equipment* is revising its recommendations to lower recommended and acceptable humidity levels to increase use of air-side economizers), users have yet to embrace it.

The conventional approach to humidifying large quantities of air requires injection of steam into air, typically from boilers or pan heaters.

BUILDING AT A GLANCE

Oracle Utah Compute Facility

Location	: West Jordan, Utah
Owner	: Oracle USA
Principal Use	: Data Center
Includes	: 25,000 ft² data center white space
Employees/Occupants	: 30
Gross Square Footage	: 164,000
Conditioned Space Square Footage	: 44,000 office space
Substantial Completion/Occupancy	: April 2011
Occupancy	: 80% of data center capacity

The generation of steam requires energy. The industry was quick to learn from its experience that it required more energy to humidify dry outdoor air than the energy saved from the use of its free cooling, and air-side economization did not make much headway in data centers. The concern with airborne contaminants and the need for increased filtration also were added reasons.

These problems were addressed efficiently in an innovative system installed in a new state-of-the-art data center in West Jordan, Utah. The first of the four 7.2 MW master planned supercells was built, leaving room for future expansion. The 25,000 ft² (2323 m²) data center is supported with a 95,000 ft² (8826 m²)

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Cold aisle showing partial un-containment at the data center.

Artist rendering of the data center.

structure to house infrastructure equipment and a 44,000 ft^2 (4088 m^2) office space. The system has operated for more than a year, and its operational fine-tuning is ongoing. Field monitored data for energy use by cooling equipment (air circulation fans and the cooling plant) for the main data center hall as well as the supporting UPS hall as a fraction of the IT equipment energy use from August 2012 to July 2013 are summarized in *Table 1*.

The cooling energy use as a ratio of the total IT equipment energy use varies from a low of 1.05 in cold weather to a maximum of 1.25 in summer, depending on the ambient wet-bulb temperature. Its partial cooling-only power utilization effectiveness (PUE:1 measured as a ratio of all cooling energy consumption divided by the IT equipment energy consumption) was measured at less than 1.05 for February and less than 1.10 for the entire year as summarized in *Table 1* and shown in *Figure 1*.

Figure 2 shows a plot of the operating partial cooling-only PUE versus daily average ambient wet-bulb temperature. The cooling energy use consisted of three components: fans for air distribution to the data hall; fans for air distribution to the UPS hall; and chiller plant to distribute trim cooling to the air-handling units. Total cooling energy required to remove each kWh of the IT equipment generated heat was quite low during periods of low ambient wet-bulb temperatures when free cooling and humidification were available, but increased when ambient wet-bulb temperatures increased as evaporating cooling needed to be supplemented with trim cooling of ambient air.

In our design and operation, we elected to operate our system with free cooling when ambient wet-bulb temperatures were generally below 52°F (11°C) (74% of hours annually) with supply air of less than 59°F (15°C). Our design rationale is discussed later. It is thought possible to obtain free cooling even at higher ambient wet-bulb temperatures approaching 65°F (18°C) (>99% of the time in this climate) since cold air can still be supplied at 72°F (22°C) with a 7°F (4°C) approach with evaporative cooling effect.

The partial cooling-only PUE varied slightly from 1.05 to 1.10 between low ambient wet-bulb temperatures of 20°F to 52°F (–7°C to 11°C). At temperatures above 52°F (11°C), we pre-cooled ambient air dry-bulb temperature just enough so that its wet-bulb temperature was 52°F (11°C). The trim cooling was provided by the chiller plant for the remaining 26% of the time. The amount of trim cooling varied – e.g., reducing wet-bulb temperature by only 1°F (0.55°C) when ambient wetbulb temperature was 53°F (12°C) to reducing it by 13°F (7°C) when ambient wet-bulb temperature was 65°F (18°C). Though the chiller was sized to run the cooling system in a complete air recirculation mode, in the event the outdoor air quality is unacceptable either due to smoke or dust particles in the air, the actual amount of trim cooling requirement was quite small, only 0.019 kWh/kWh of the IT energy on annual basis. The energy consumption for chiller plant versus ambient wet-bulb temperature is also shown in *Figure 2*. The overall partial cooling-only PUE is very attractive compared to the industry averages.

Since 100% or a very large fraction of outdoor air is used all

Table 1: Energy use by components of cooling equipment as a fraction of the IT equipment energy use (partial PUE of cooling equipment).

COOLING EQUIPMENT ENERGY USE PER UNIT IT ENERGY CONSUMPTION				
MONTH	ELECTRICITY USE BY AIR MOVING FANS IN DATA HALL, KWH/KWH OF THE IT EQUIPMENT	ELECTRICITY USE BY AIR MOVING FANS IN UPS HALL, KWH/KWH OF THE IT EQUIPMENT	ELECTRICITY USE BY CHILLER COOLING PLANT, KWH/KWH OF THE IT EQUIPMENT	TOTAL ELECTRICITY USED FOR COOLING DATA CENTER, KWH/KWH OF THE IT EQUIPMENT
Jan 13	0.058	0.009	0.001	0.068
Feb 13	0.040	0.010	0.000	0.050
Mar 13	0.050	0.011	0.006	0.066
Apr 13	0.053	0.010	0.002	0.065
May 13	0.071	0.011	0.002	0.084
Jun 13	0.099	0.013	0.018	0.130
Jul 13	0.114	0.014	0.113	0.242
Aug 12	0.087	0.020	0.070	0.178
Sep 12	0.068	0.017	0.019	0.104
Oct 12	0.054	0.014	0.000	0.069
Nov 12	0.053	0.013	0.000	0.067
Dec 12	0.049	0.012	0.000	0.061
Annual	0.067	0.013	0.019	0.099

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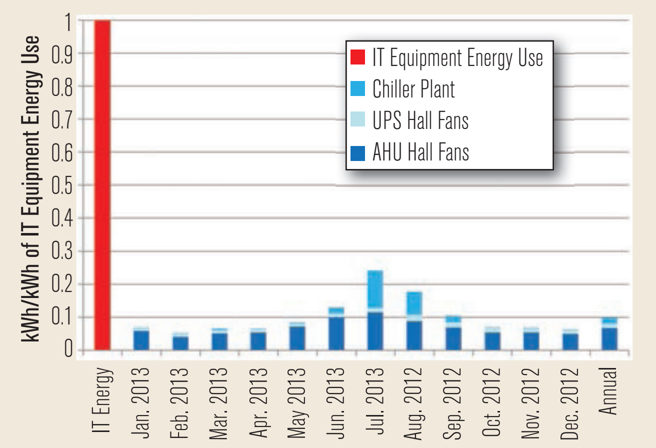

Figure 1: Plot of energy use by components of cooling equipment as a fraction of the IT energy consumption (contributing components of the partial PUE).

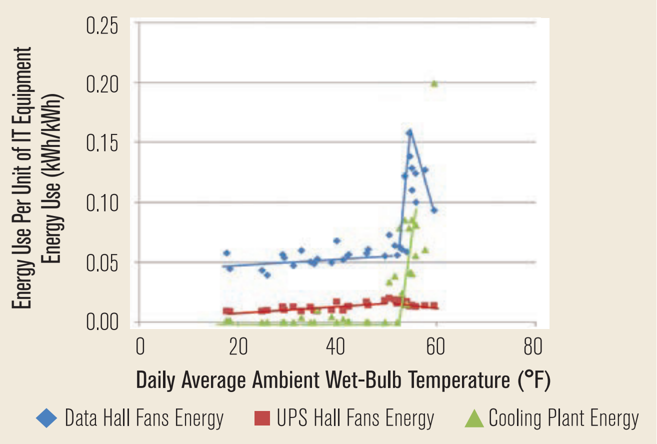

Figure 2: Cooling energy use vs. ambient wet-bulb temperature.

the time unless we need to run the system in recirculation mode, the indoor air quality is excellent. The air flows over a wet media that captures dust particles and also provides excellent filtration of outdoor contaminants as well as enhanced indoor air quality.

So far, we have never had to run the system in a complete recirculation mode.

Innovations in Energy Efficiency

Several innovations, as well as best practices we learned from operating other data centers, were implemented here.

Humidification

The system uses the waste heat from the IT equipment to evaporate water into moisture instead of using energy to generate steam. Moving hot dry air over a wet media to cool it is a well-known technology, but its use to primarily humidify air has not yet found its way in the industry. The hot air from the IT equipment, mixed with cold outdoor dry air, flows over a wet media where it picks up moisture and gets humidified as shown in *Figure 3*.

The air is cooled in the process, which is also known as evaporative cooling. The cooling is certainly helpful but incidental in this application; the primary objective is to get free humidification. In West Jordan, Utah, humidification is needed for more than 78% of the hours in a year when outdoor dew-point temperature is below the current minimum acceptable dew-point temperature of 41.9°F (5.5°C) as shown in *Table 2*, which also shows a quick comparison of number of hours when free cooling is available with conventional air-side economizer as well as with the installed cooling system.

The solution provides complete free humidification and cooling for 74% of the time and partial free cooling for the remaining 26% of the time with the controls setpoints that we had selected. It has the ability to provide free cooling and humidification for 99% of the time if supply air temperatures of 72°F (22°C) are acceptable.

In comparison, the conventional economizer provides free cooling for only 73% of the time, but requires humidification energy for 78% of the time. The large number of hours when humidification is needed in cold climates explains why conventional humidification systems with steam required more energy than cooling energy saved from cold outdoor air, and economization was shunned by the industry.

Controls

Conventional controls are based on dry-bulb temperatures and use feedback from the discharge air temperature to control sensible cooling. The innovation in controls is based on using the wet-bulb temperature of the incoming air for control of humidification. This also provides stable supply air temperature and prevents wet/dry cycling of the evaporative media and associated wide variation in supply air humidity and temperatures.

The simplicity of controls lies in the fact that the return/ exhaust air is mixed with the incoming outdoor cold air to continually achieve a desired wet-bulb temperature.

The mixed air then passes over a wet media to achieve stable supply air temperature.

We allowed the mixed air wet-bulb temperature to float between a minimum and a maximum setpoint.

The maximum setpoint was based on our air-distribution effectiveness. When the outdoor air wet-bulb was within the range, no mixing was needed. When outdoor wet-bulb temperature exceeded the maximum setpoint, the chiller plant was activated to pre-cool incoming air, which reduced its dry-bulb as well as wet-bulb temperatures.

In most scenarios, only small amounts of sensible cooling of the dry air ambient air was sufficient to bring its wet-bulb temperature to desired levels.

The amount of cooling required was only that which was needed to trim outdoor air wet-bulb temperature to the desired level, which is much smaller than what would be needed to provide 100% cooling of the recirculation air. This explains why the chiller plant was not required for most of the year except during the hot months of July and August and even then the amount of cooling energy required was small, as shown in *Table 1* and *Figures 1* and *2*.

Cold Air Distribution and Uncontainment

We turned a design oversight into an asset. Containment of hot air or cold air and preventing mixing between the two in the data center space is now widely accepted. However, we intentionally

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chose not to fully isolate cold and hot airstreams, but allowed some directed mixing between the two in the data center space to overcome design limitation and gain energy efficiency. This may sound counterintuitive to the now widely accepted practice of fully isolating hot and cold air, but its rationale is explained below and it is providing excellent energy savings in the field. For the record, in 2004 the author was likely the first one to demonstrate and champion the use of physical barriers between hot and cold airstreams to prevent its mixing at Oracle's large data center in Austin, Texas.[2,3] For proper functioning of any containment, the airflow across the IT equipment must be equal to the airflow across the cooling equipment. If not, either the airflow over the IT equipment will starve or airflow over the cooling equipment will starve. Therefore, the airflow of the cooling equipment must be sized to meet the airflow of the IT equipment. The airflow over IT equipment is derived from the design temperature rise when air passes through it. The average design temperature rise in IT equipment is ever-increasing as it becomes more power consuming. Our data center was designed to handle the latest IT hardware, and most of these are designed with lower airflow and higher temperature rise of ~30°F (17°C) across the IT equipment.

The cooling equipment air-handling units were sized to match the lower airflow for a 30°F (17°C) temperature rise. However, we noticed that the average temperature rise across our current IT equipment was less than 20°F (11°C). This meant that we needed to increase the airflow capacity or size of our air-handling equipment by 50% to use full containment. This posed a major dilemma: redesign the entire data center, including all mechanical, civil and electrical infrastructures with 50% larger air-handling equipment. This would increase the data center infrastructure costs substantially as well as delay the project, which this fast-track project could not afford.

We used a very creative approach – un-containment – to overcome this problem. Instead of redesigning the entire data center with full containment, we chose to use only a partial barrier between the cold and hot air, which allowed some directed mixing of hot air back into the cold aisles. This permitted us to supply less cold air to the data center, which after mixing with some of the recirculated hot air within the data center space, met the total airflow requirement of the IT equipment. Therefore, it allowed us to supply lesser quantity of colder air and still be able to use our smaller sized central air-handling unit and cooling system infrastructure without redesign and at much lower first cost.

The smaller AHU fans also significantly reduced air distribution fan power. The cold climate of Utah allowed us to supply below 59°F (15°C) free cold air for 74% of the time. For the remaining 26% of the time, only trim cooling was used. This turned out to be a very cost effective (smaller size AHUs, smaller civil structure and space, etc.) as well as energy efficient (less airflow with free cooling for 74% of the time) solution. The low airflow quantity at lower temperature supply air has helped us achieve such low operating partial cooling PUEs in cold, as well as warm but dry weather. The partial uncontainment in a cold aisle is shown in *Figure 4*.

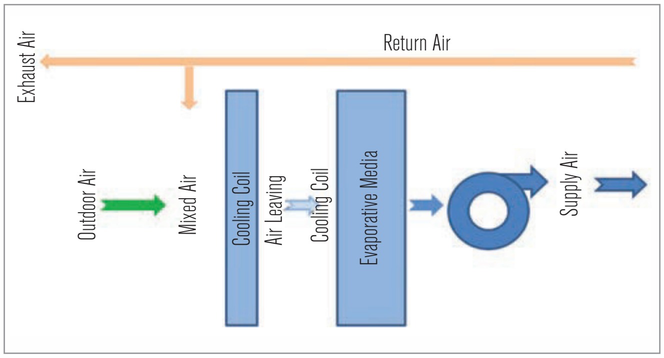

Figure 3: Schematic of air-handling unit.

Table 2: Number of hours in a year when free cooling is available in Salt Lake City.

	Conventional airsideeconomizer	Innovative economizer
Number of hours of 'free' cooling (<67.5°F)	73%	99%
Number of hours backup cooling needed	27%	1%
Number of hours humidification energy needed	78%	0%

The supply air temperature was further allowed to float to below 59°F (15°C) to take advantage of the free cooling in this cold climate by reducing fan speed and thus fan energy consumption, and counting on the recirculation hot air to make up the remaining requirement. As can be seen in *Figure 2*, the fan power required for air distribution in the data hall and the UPS hall are lower when ambient wet-bulb temperatures are lower and rise slowly as the wet-bulb temperature increases. Due to some situations in our controls, we noticed that the amount of required airflow increased rapidly when supply air temperatures reached near ~59°F (15°C), or wet-bulb temperatures reached ~52°F (11°C). Once the trim cooling was turned on and the supply air temperature was reduced below ~59°F (15°C), the fan power reduced again. We are working on our controls sequences to overcome this quirkiness.

A thermograph of temperature profile at the inlet of the rack is shown in *Figure 5*. The cold air is delivered through overhead duct. Since we have a partial barrier and not a complete isolation between cold supply and hot return air, hot air is allowed to seep into the cold aisle, which can be seen in the temperature profile of inlet air to the IT equipment. A low temperature of about 60°F (15.5°C) near the bottom of the rack and a high of about 80°F (27°C) near the top of the rack was observed.

Figure 6 shows a thermographic image of the inlet and discharge air to IT equipment. The average ΔT across this IT equipment of about 27°F (15°C) is representative of newer IT equipment. However, the average ΔT across all IT equipment, including new and legacy compute, storage and networking IT equipment was about 18°F (10°C).

So, we are only supplying about two-thirds of the primary airflow from the air-handling unit at low temperature of ~59°F (15°C), and counting on about one-third of the hot air to recirculate in the cold aisle. This allowed us to undersize our AHUs and associated infrastructure by one-third. It also reduced the fan

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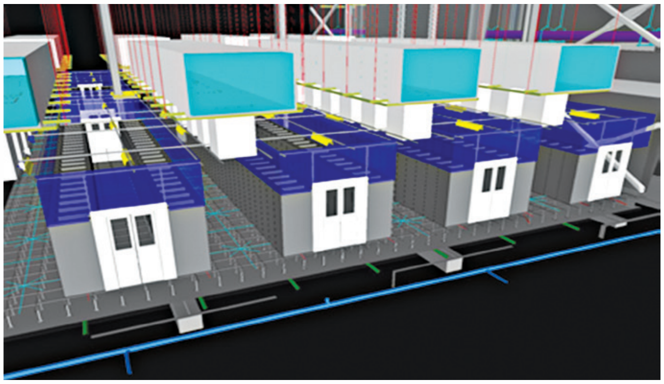

Figure 4: Un-containment air distribution

power requirement. As mentioned earlier, free cooling is available for more than 74% of the time in this cold climate and trim cooling is needed for the remaining time. But the overall operating energy consumption is quite attractive, as shown in *Table 1* with partial cooling-only PUE of less than 1.06 in winter and 1.10 annually.

Trim Cooling with Chiller

The placement of cooling coils as shown in *Figure 3* in the air-handling units is such that it pre-cools ambient air in summer just enough so that its wet-bulb temperature reaches our desired level. For example, no cooling is needed when outdoor temperature is 90°F (32°C) but outdoor air dew-point temperature below 42°F (5.5°C).

At temperatures warmer than 90°F (32°C) on hot dry days with outdoor air dew-point temperature below 42°F (5.5°C), we need to cool air only to 90°F (32°C).

Besides requiring less amount of cooling, this also allows the chilled water temperature to be much higher than conventional 45°F to, say 65°F or warmer, and the chiller system to run much more efficiently.

Overhead Air Distribution

This prevents uncontrolled leakage around cable cuts in raised floors that we observed in our other data centers.

Operation and Maintenance

The novel controls prevent frequent dry/wet cycling of the evaporative media, improve its performance and extend its life. Since we are primarily moving air and circulating water in the evaporative media, and do not need chiller or mechanical cooling most of the time, the operation and maintenance is far less than systems that require mechanical cooling. The simplicity of the control scheme is a further asset.

Cost Effectiveness

Since the system requires only evaporative media and could run on it for 99% of the time if designed with the right airflow quantity, it is a very cost effective solution. Oracle, however, chose to have a 100% backup mechanical cooling system just in case it was ever needed in the event of fire or other natural calamity that prevented the use of outdoor air. But once the chiller system was selected, we leveraged it and planned its use in the summer to supply colder air, which coupled with partial un-containment, helped us select smaller AHUs by one-third and provided a significant first cost savings on AHU equipment and the civil structure to house it as well as additional operating cost savings from smaller fans. However, chillers are not planned in the next phase.

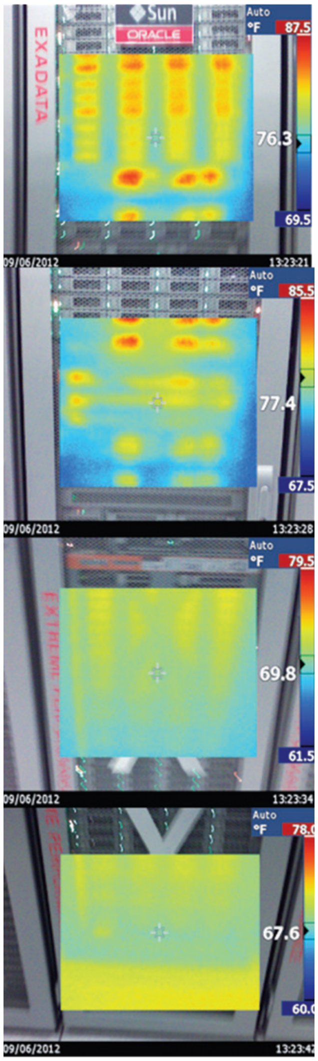

Figure 5: Thermograph of temperature profile at IT rack inlet.

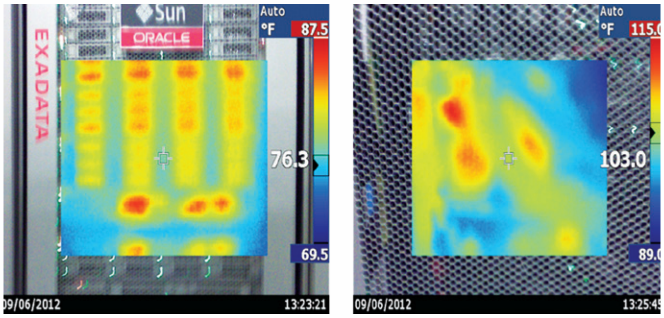

Figure 6: Thermograph of temperature profile at rack discharge.

Environmental Impact

With such efficient operation and low operating PUE, the system is expected to save over 41,000 MWh a year and 37,000 metric tons equivalent CO_2 annually compared to average efficient data center when in full operation.

Independent Verification of Performance

The system's operating performance was independently verified by diligently analyzing the field performance data by the electric power utility, Rocky Mountain Power, and its consultant. It also received significant incentive payment based on its measured field performance.

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References

1. The Green Grid. "PUE: A Comprehensive Examination of the Metric." White paper #49.
2. Khattar, M. 2010. "Data center retrofit: heat containment and airflow management." ASHRAE Journal (12):40–49.
3. Martin M., M. Khattar M., M. Germagian. 2007. "High density heat containment." ASHRAE Journal (12)38–43.