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EXPERIMENTAL ANALYSIS OF CHILLER COOLING FAILURE IN A SMALL SIZE DATA CENTER ENVIRONMENT USING WIRELESS INSTRUMENTATION

Mohammad Tradat
State University of New York at Binghamton- SUNY
Binghamton, NY, USA

Bahgat Sammakia
State University of New York at Binghamton- SUNY
Binghamton, NY, USA

Husam Alissa
Microsoft
Redmond, WA, USA

Kourosh Nemati
Future Facilities Ltd.
San Jose, CA, USA

ABSTRACT

Given the vital rule of data center availability and since the inlet temperature of the IT equipment increase rapidly until reaching a certain threshold value after which IT starts throttling or shut down because of overheat during cooling system failure. Hence, it is especially important to understand failures and their effects. This study presented experimental investigation and analysis of a facility-level cooling system failure scenario in which chilled water interruption introduced to the data center. Quantitative instrumentation tools including wireless technology such as wireless temperature and pressure sensors were used to measure the discrete air inlet temperature and pressure differential though cold aisle enclosure, respectively. In addition, Intelligent Platform Management Interface (IPMI) and cooling system data during failure/recovery were reported. Furthermore, the IT equipment performance and response for opened and contained environments were simulated and compared. Finally, an experiment based analysis of the Ride Through Time (RTT) of servers during chilled water interruption of the cooling infrastructure presented as well. The results showed that for all three classes of servers tested during the cooling failure, CAC helped keep the server's cooler for longer. The containment provided a barrier between the hot and cold air streams and caused slight negative pressure to build up, which allowed the servers to pull cold air from the underfloor plenum. In addition, the results show that the effect of CAC in containment solutions on the IT equipment performance and response could vary and depend on the server's airflow, generation and hence types of servers deployed in cold aisle enclosure. Moreover, it was shown that when compared to the discrete sensors, the IPMI inlet temperature sensors underestimate the Ride Through Time (RTT) by 42% and 12% for the CAC and opened cases, respectively.

Keywords: Chilled Water Interruption, Data Center, Wireless Technology, Ride Through Time.

NOMENCLATURE

CAC	Cold Aisle Containment
CPU	Central Processing Unit
CRAH	Computer Room Air Handler
DC	Data Center
DCIM	Data Center Infrastructure Manager
IPMI	Intelligent Platform Management Interface
IT	Servers, Switches, Blades, …
NR	Not Reach
RPM	Revolution Per Minute
RTT	Ride Through Time
SAT	CRAH Supply Air Temperature
T_{A2}	ASHRAE A2 Upper Dry Bulb Temperature Limit (35 °C)
UPS	Uninterruptable Power Supply
WPS	Wireless Pressure Sensor
WTS	Wireless Temperature Sensor

INTRODUCTION

Typically, data centers are designed with an Uninterruptable Power Supply (UPS) to provide instantaneous power to the IT equipment in the event of a power failure. However, the cooling infrastructure usually relies on the backup generators during a power failure. Whereas the UPS batteries continue to operate the IT equipment, which means continued heat dissipation to the facility, the generator control system can take up to 10-20 seconds (or longer) to return cooling to acceptable levels for the IT equipment. [1].

Characterizing the data center (DC) performance during failure or normal operation can be done either analytically or experimentally. Numerous studies [2-5] took an analytical approach to extracting data center performance metrics, using parameters such as aisle enclosure deployment, supply air temperature, temperature increase across IT, and fan control strategy of the IT equipment. Other studies discussed experimental measurements using a mobile measurement tool to characterize the thermal conditions and flow components of the data center [6-7].

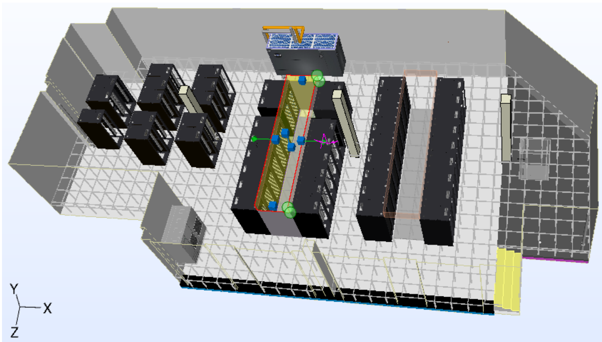
In its many forms, aisle containment provides a physical barrier between the supplied cool air and the cabinet hot exhaust air. This optimizes the airflow distribution in the data center room by preventing the cold and hot air streams from mixing. Over the past decade, containment has been popularized by a strategy only considered practical for high thermal loads [8-12], to one of the most widely used strategies for DCIM. Per the 2014 Uptime Institute Survey [13], 80% of the 1,000 data center operators and IT practitioners surveyed indicated that their use of cold or hot aisle containment improved data center efficiency. The wide use of containment has also driven numerous research efforts to understand its various components [14-19]. Shrivastava et al. [14] compared different types of containment systems from the perspective of the cooling energy cost and performance. In addition, guidelines for choosing suitable containment arrangements were introduced. Patterson et al. [15] investigated the effect of entrained warm air in cold aisle containment (CAC). Their results showed that recirculation significantly affected the inlet of the lowest servers. Shrivastava and Ibrahim [1] showed the positive impact of CAC systems on the Ride Through Time (RTT) during failure. They showed that the CAC systems increase the RTT five times. Alissa et al. [16] provided quantitative and qualitative measurements for data center transient performance during a cooling failure in open and contained environments. Their results showed different responses for the IPMI data, fan RPM, CPU temperature and internal server temperature sensors during failure for CAC versus the case of the open aisle. In addition, they concluded that the RTT was overestimated by 70% based on the external inlet air temperature and that these temperature fields did not reflect the IT equipment's thermal performance. Makwana et al. [17] investigated the importance of containment sealing. They stated that sealing containment maximizes the benefits of CAC. Sundaralingam et al. [18] used a multi-dimensional array of sensors for airflow management in the CAC system. They suggested that selecting CAC based on only the rack inlet temperature may not be a best practice. In addition, the authors recommended over-provisioning for fully sealed contained aisles. Muralidharan et al. [19] investigated the impact of CAC on the thermal performance of data centers. The authors quantified the thermal impact of CAC by comparing it with different open arrangements (open hot aisle/cold aisle). The study considered different cabinet heat loads at two different Computer Room Air Handler (CRAH) unit Return Air Temperature (RAT) set points. Their results showed a 22% savings in energy when using the CAC systems rather than the conventional open hot aisle/cold aisle.

The true benefit of containment lies in the separation of the cold and hot air streams, which provides the opportunity to closely match cooling airflow to IT equipment airflow, thereby promoting a uniform cabinet inlet temperature profile. It also enables the cold air supply temperature to be increased, while concurrently maintaining the inlet temperatures at levels acceptable for the IT equipment. This translates to cooling energy savings and increased cooling efficiency [20]. Therefore, to truly gain the benefits of containment, an effective monitoring system must be used to accurately measure IT equipment inlet temperatures, as well as IT equipment airflow needs. Nishi et al. [21] addressed the cooling inefficiency resulting from airflow mismatch between the cooling requirements of the IT equipment and the supply air conditions from the facility-cooling infrastructure. They proposed and outlined a method to estimate the real-time volumetric airflow based on fans' RPM data. Then, the estimated volumetric airflow and IT exhaust temperature were used as input parameters to the Intel Data Center Manager (DCM) by using the IPMI commands. Alissa et al. [22] showed that the server's IPMI average fan speed and discrete pressure reading from containment can be used to generate a flow curve model. This model collapses the server impedance and effective total fan curve into one. The flow curve can be used in real time airflow prediction that is inclusive of all operational CAC pressure differential values. Tradat et al. [23] showed that the difference between the discrete and IPMI inlet temperature of the IT equipment increased as SAT increased. This was due to the negative pressure differential inside containment. Furthermore, the authors identified a value of the supply air temperature at which the IT equipment fans speed up.

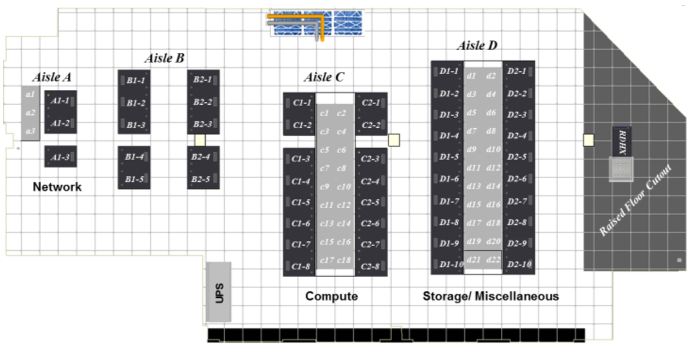
This study presents an experimental based investigation and analysis for both cold aisle (CAC) and opened (no CAC) configurations on IT equipment RTT during chilled water interruption scenario, referred as a cooling failure. In addition, it simulates and compares the IT equipment performance and response for both configurations.

DATA CENTER LABORATORY

The ES2-Binghamton University Data Center Laboratory was used for all the testing conducted for this study. The lab is a 2,315 ft^2 (215 m^2) space with a 3 ft. (0.91 m) raised access floor. It is equipped with a down-flow chilled water-based cooling unit, which is rated at 32 tons (114 kW) of cooling capacity and 16,500 CFM of airflow capacity. The unit is equipped with a variable frequency drive on its blower motor so that airflow can be modulated. IT equipment cabinets are placed in the laboratory in a traditional alternating hot aisle/cold aisle arrangement. Aisle C, of primary interest in this study, as it is a contained cold aisle with end-of-aisle doors and a horizontal barrier across the aisle at the cabinet tops. A layout of the lab is shown in Figure 1. [23].



(a)



(b)

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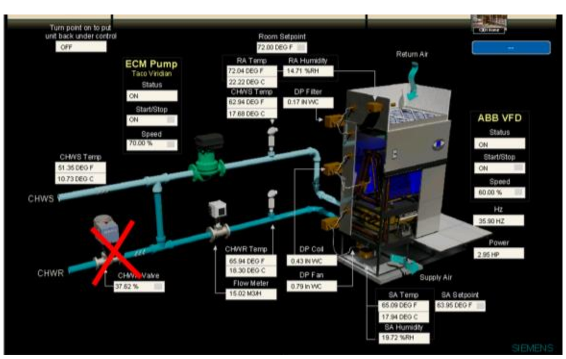


(d)

Figure 1. (a) Data center laboratory layout. (b) Aisle C tiles and rack matrix. (c) Wireless temperature sensors location [at server's inlet] (d) CRAH unit chilled water loop.

Aisle C is comprised of two rows, with 8 cabinets per row. A total of 206 IT servers are deployed in the 16 cabinets of Aisle C, and all empty RU slots were blanked off. Server types and quantities used in Aisle C are listed in Table 1.

Table 1. Aisle C IT Inventory. [23].

IT Make	Number	Unit Active power[W]
Dell^{TM}PowerEdge^{TM}2950	128	386
Dell^{TM}PowerEdge^{TM}R520	64	165
Dell^{TM}PowerEdge^{TM}C2100	14	281

MEASUREMENTS METHODOLOGY

The differential pressure between contained Aisle C and the laboratory air space was measured using a wireless pressure sensor (WPS). Discrete air temperatures were gathered using a wireless temperature sensor (WTS) as shown in Figure 1 (c), they start data acquisition at a prescribed time. They were located at the inlets of the IT servers with a measurement uncertainty of ±0.5 °C depending on the temperature range. The inlet air temperatures were also reported by IT equipment using IPMI data. The IPMI data also included the server fan speed, CPU temperature, and active power.

EXPERIMENTAL SETUP

For all tested scenarios, the IT servers were stressed at 100% CPU utilization through the Linux operating system, resulting in a total IT power consumption of 74 kW. The cooling unit supply air temperature setpoint was 59 °F (15 °C). The cooling unit blower speed always set at 100% VFD. Initially neutral or slightly positive pressure maintained in CAC. This measurement was treated as an indicator of balanced volumetric airflow. That is, the amount of air being supplied into Aisle C by the cooling unit was equal to, or slightly higher than, the amount of air being drawn through the servers in Aisle C. Before starting each test scenario, the above conditions were maintained for an extended period to ensure that a steady state condition had been achieved. Once steady state was reached, the chilled water was deliberately interrupted while the IT servers were kept running. The discrete temperature sensors were monitored until an average IT server inlet temperature reached close to the ASHRAE allowable temperature for class A2 servers of 35 °C, after which the cooling unit chilled water was restored and maintained until a steady state was reached once again. The tests included two scenarios The first was testing the IT equipment response in the contained environment (CAC)). The second was testing the IT equipment response in the opened environment (no CAC).

RESULTS AND DISCUSSION

PRESSURE DIFFERENTIAL

This section focuses on analyzing the pressure differential data across Aisle C for the first scenario. The data is presented in Figure 2. The figure shows that the pressure differential starts with a neutral/slightly positive pressure differential in Aisle C. at the beginning of cooling failure the pressure differential remains constant for about 15 ± 1 minutes then it continuously decrease to reach slightly negative values due to the increase in the servers fan speed. When the cooling unit chilled water restored IT equipment starts to receive cooler air and hence fans decelerate to restore the slightly positive pressure.

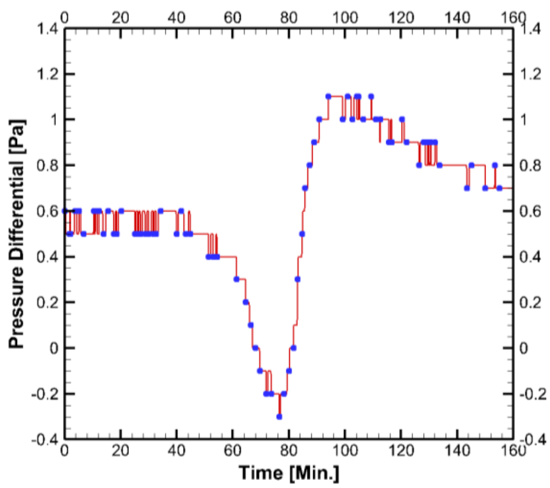


Figure 2. CAC Pressure Differential.

IPMI RESPONSE

This section focuses on the IPMI telemetry from the servers (inlet temperatures, CPU temperatures, and fan speed). One of the advantages noted for the IPMI temperature data is that it is reported by each server, which is the case with all the servers used in this study. The challenge then becomes how to use the telemetry from 206 servers and draw meaningful conclusions regarding a critical event in data center operations such as a cooling failure. Thus, servers were selected from each make and model that had the highest reported IPMI inlet temperature. This strategy ensures that all servers will be operating at acceptable temperature readings. These servers will be referred to as the critical servers. The servers were run in normal operation mode and therefore the individual server fans were controlled by the server fan control algorithm, thus some of the server fans changed speed with changes in air temperature. The location of the servers in the rack was not a factor in determining criticality. For example, the Dell PowerEdge 2950 server (Dell PowerEdge 2950-016) located at the top of the rack C1-1 reported the highest IPMI inlet temperatures. However, the other two Dell models that reported the highest IPMI inlet temperatures were located at the top of the rack; namely rack C2-6 (server R520-13) and rack C2-8 (server C2100-01). These servers were defined as the critical servers and will be used for further analysis.

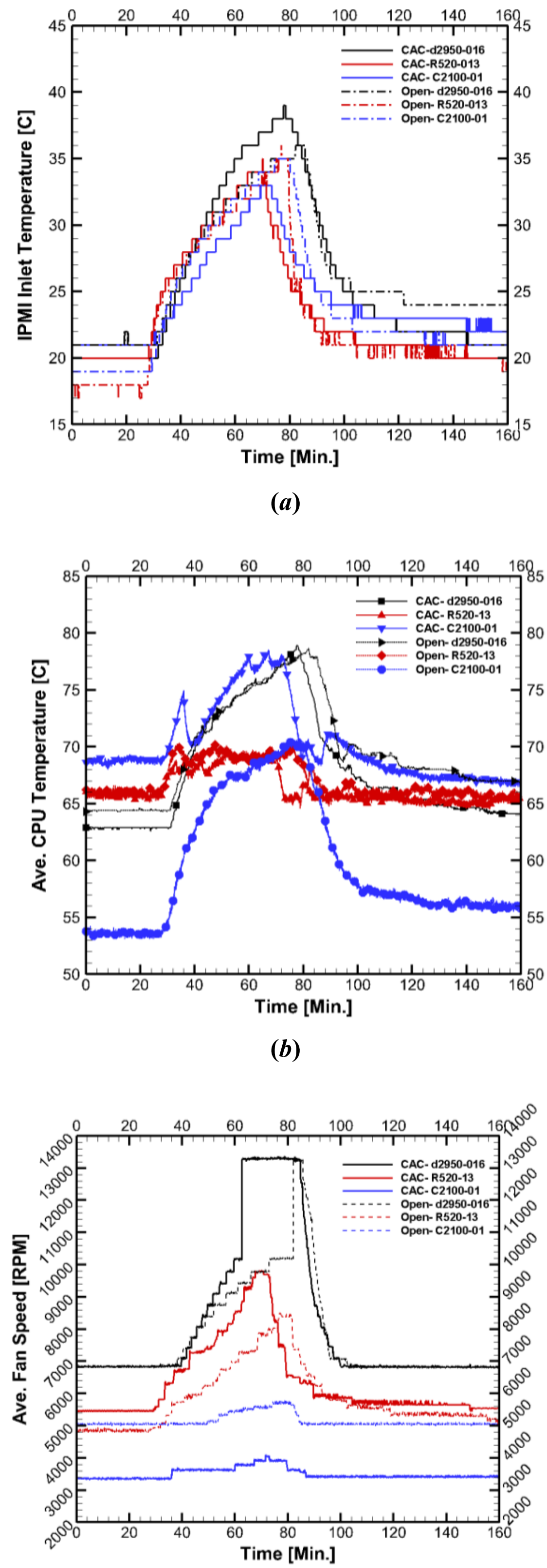


Figure 3. (a) IPMI inlet temperature. (b) Ave. CPU temperature. (c) Server Ave. fan speed.

Figure 3 (a) shows the behavior of the inlet temperature as reported by the IPMI protocol of the critical servers (d2950-016, R520-13, and C2100-01) for both opened and CAC scenarios. It can be noted that the value and gradients of the IPMI inlet temperature for the d2950-016 for CAC case are always higher than those for the same server for the opened case, where the maximum reported values are 35℃ and 39℃ for opened and CAC respectively with a delta of 4℃. All the d2950 model servers show very similar behavior to the critical server regardless of location. Previous studies have shown that this is mainly due to the internal recirculation that affects the IPMI inlet temperature sensor for this server model. This recirculation result from the internal design of such servers that allows a recirculation path from the power supply side since the power supply fan is inadequate to overcome the external resistance of the CAC when a cooling failure event takes place. The change in pressure results from the server fans accelerating between low and high values so the reduction in airflow rate decreases as discussed in [22, 27]. Furthermore, by comparing the IPMI data of the d2950-016 for both tested scenarios, it can be noted that the curves start to deviate at the point where the neutral pressure is lost, which indicates a correlation with the induced back pressure. The other two models of servers (R520 and C2100) have minimal differences in temperature data. The internal design differences between the server models directly impact how they respond to increased external resistance.

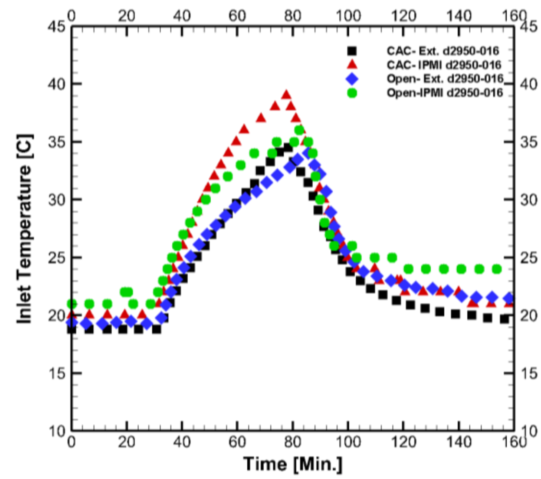
Given the critical nature of the CPU, its data, which is provided by the IPMI protocol, has been analyzed. Figure 3 (b) shows the Average CPU temperature for all classes of servers in Aisle C. It can be noted that for the d2950 and the R520 server's model average CPU temperatures reported similar behavior for both scenarios (opened and CAC). However, it can be noted that for the C2100 server model has a different response. If the average CPU temperature of this model is normalized then the opened case reported higher average CPU temperature in such cooling failure scenario.

Figure 3 (c) shows the server fan speed behavior for all types of servers in Aisle C for both test scenarios. As cooling failure takes place, the server's fans start to accelerate to compensate for the temperature increase. The figure indicates that for the CAC case the d2950 servers' fans ramp up faster than for the opened case, which was the case for the R520 server class and not the for the C2100 server class This is most likely due to differences in the fan algorithm used for each model of server.

IPMI VS DISCRETE RESPONSE

This section focuses on comparing the IPMI and discrete inlet temperature data for the three critical servers identified in the previous section. Figures 4 (a), (b), and (c) show the inlet temperatures for both opened and CAC scenarios of the d2950-016 server, R520-13 server, and C2100-01 server, respectively. The discrete inlet temperature data exhibited the same behavior for all three server models. The data shows that having contained aisle, kept the contained aisle cooler for an extended period after failure than in the case of no CAC. This is attributed to the slight negative pressure buildup inside containment (Figure 2) and the IT equipment ability to pull the cool air from the plenum space. The plenum space act as a cold air reservoir from which the IT equipment can pull air during a cooling failure. However, the opened case, the servers are pulling air from the warm air in the room, causing the server inlet temperatures to rise quicker. Therefore, based on the discrete sensor data, having the aisle contained during failure helps the servers stay cooler for longer, and provides a longer RTT.

The IPMI inlet temperature data exhibited a different behavior. For servers, R520-13 and C2100-01, figure 4 (b) and (c) respectively, the IPMI inlet temperature data were the same for both tested cases. However, the IPMI inlet temperature data for the d2950 server in Figure 4 (a) shows in the CAC case, the server inlet temperatures rise much faster than that for the opened case. Therefore, based on the IPMI inlet temperature data for the d2950 server, the containment during failure provides a shorter RTT.



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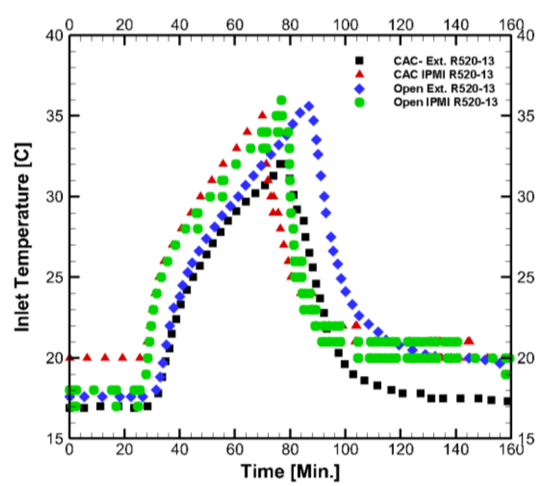

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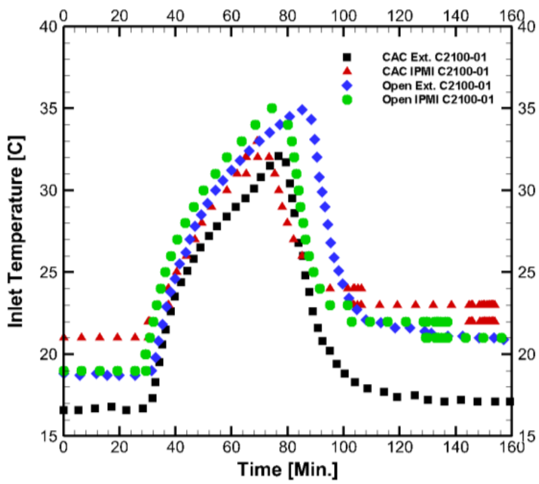

(c)

Figure 4. IPMI vs Discrete inlet temperature (a) d2950-016. (b) R520-13. (c) C2100-01.

UPTIME ANALYSIS

Tables 2 and 3 present a comparison of the estimated uptime (RTT) for CAC and opened cases, respectively. The tables provide the uptime numbers using both the discrete sensors inlet temperature data, and IPMI inlet temperature data for all three classes of servers in Aisle C using the reported data shown in figures 4 (a), (b) and (c). It can be noted that for CAC case the IPMI inlet temperature sensors underestimate the RTT by ~ 42% (T_{A2} threshold) compared to the estimated RTT through the discrete monitoring sensor for the d2950 server. In contrast, for the opened case it underestimates the RTT only by ~ 12% compared to that estimated through discrete sensors for C2100 server.

Table 2. Ride Through Time CAC Scenario Comparison [Min.].

Threshold	Ext. T_{in}			IPMI T_{in}		
	d2950	R520	C2100	d2950	R520	C2100
Failure – 27 °C	18	20	16	10	9	16
Failure – 32 °C	36	46	46	22	26	34
Failure – 35 °C	52	NR	NR	30	42	NR

Table 3. Ride Through Time Opened Scenario Comparison [Min.].

Threshold	Ext. T_{in}			IPMI T_{in}		
	d2950	R520	C2100	d2950	R520	C2100
Failure – 27 °C	18	19	14	10	9	11
Failure – 32 °C	40	30	34	26	28	29
Failure – 35 °C	NR	38	50	45	43	44

CONCLUDING REMARKS

This study presented an experimental based analysis on the ride through time (RTT) of servers during a chilled water interruption scenario, referred as a cooling failure. Two cases were tested to understand, simulate and compare the IT equipment performance and response to both cases during cooling failure. The first case was cold aisle containment. The second was an opened environment (no CAC). The results showed that for all three classes of servers tested. During cooling failure, CAC helped keep the servers 'cooler for longer. The containment provided a barrier between the hot and cold air streams and caused negative pressure to build up, which allowed the servers to pull cold air from the underfloor plenum. In addition, the results show that the effect of CAC in containment solution on the IT equipment performance and response could vary and depend on the server's airflow, generation and hence types of servers deployed in cold aisle enclosure. The results also showed that when compared to the discrete sensors, the IPMI inlet temperature sensors underestimate the Ride Through Time (RTT) by 42% and 12% for the CAC and opened cases, respectively.

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