The Impact of Cold Aisle Containment Pressure Relief on IT Availability

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Abstract

During the lifespan of a data center, power outages and blower cooling failures are common occurrences. Given that data centers have a vital role in modern life, it is especially important to understand these failures and their effects. A previous study [16] showed that cold aisle containment might have a negative impact on IT equipment uptime during a blower failure. This new study further analyzed the impact of containment on IT equipment uptime during a CRAH blower failure. It also compared the IT equipment performance both with and without a pressure relief mechanism implemented in the containment system. The results show that the effect of implementing pressure relief 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 32%. This means that the RTT calculations based on the IPMI inlet sensors may be inaccurate due to variations in the sensor readings; as they exist today; in these servers. as discussed in a previous study [26].

Additionally, it was shown that all Dell PowerEdge 2950 servers have a similar IPMI inlet temperature reading, regardless of mounting location. As external system resistance increases during cooling failure, the servers exhibit internal recirculation through their weaker power supply fans, which is reflected in the high IPMI inlet temperature readings. For this server specifically, a pressure relief mechanism reduces the external resistance, thereby eliminating internal recirculation and resulting in lower IPMI inlet temperature readings. This in turn translates to a lower RTT. However, pressure relief showed conflicting results where the discrete sensors showed an increase in inlet temperature when pressure relief was introduced, thereby reducing the RTT. The CPU temperatures conformed with the discrete sensor data, indicating that containment helped increase the RTT of the servers during failure.

Keywords:
Cooling Failure, Data Center, Cold Aisle Containment, IPMI, Uptime, Pressure Relief.

Nomenclature

CAC	Cold Aisle Containment
CPU	Central Processing Unit
CRAH	Computer Room Air Handler
DC	Data Center
DCIM	Data Center Infrastructure Management
FD	Free Delivery (Design) Airflow
HAC	Hot Aisle Containment
IPMI	Intelligent Platform Management Interface
IT	Servers, Switches, Blades, …
NR	Not Reach
PDU	Power Distribution Unit
RAT	Return Air Temperature
RPM	Revolution Per Minute
RTT	Ride Through Time
SAT	Supply Air Temperature
T_{A1}	ASHRAE A1 Upper Dry Bulb Temperature Limit (32 °C)
UPS	Uninterruptable Power Supply

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].

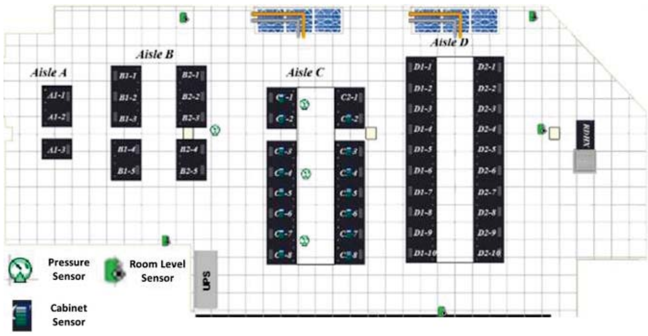
In its many forms, aisle containment provides a physical barrier between the supplied cool air and the cabinet hot exhaust air. This optimizes the airflow distribution in the data center room by preventing the cold and hot air streams from mixing. Over the past decade, containment has been popularized from 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 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 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. To the authors' knowledge, the impact of using a pressure relief mechanism during an airside cooling system failure is scarcely examined in available literature.

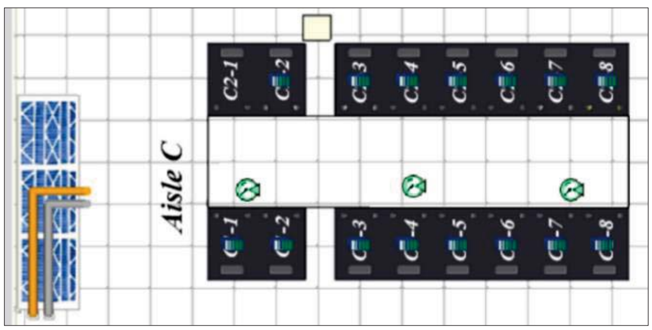
This study presents an experimental based investigation and analysis for the effects of a contained cold aisle environment on IT equipment RTT during CRAH blower failure scenarios. In addition, it simulates and compares the IT equipment performance and response with the introduction of a pressure relief mechanism.

Facility Description

The ES2-State University of New York at Binghamton 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 two down-flow chilled water based cooling units, each rated at 32 tons (114 kW) of cooling capacity and 16,500 CFM of airflow capacity. Both units are equipped with a variable frequency drive on their 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, is of primary interest in this study, as it is a contained cold aisle with end-of-aisle doors and a horizontal barrier across the top of the aisle that is level with the height of the cabinets. A layout of the lab is shown in Figure 1. [26].



(a)



(b)

(c)

Figure 1. (a) Data center laboratory layout including temperature and pressure sensors locations as shown in **SynapSoft™**. (b) Aisle C tiles and rack matrix. (c) Discrete sensors locations per rack [red circles].

Aisle C is comprised of two rows, with eight cabinets per row. A total of 242 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. [26].

IT Make	Quantity	Unit Active power[W]
Dell™PowerEdge™2950	128	386
Dell™PowerEdge™R520	64	165
Dell™PowerEdge™C2100	14	281
HP ProLiant DL385 G2	36	330

Measurements Methodology

Differential pressure between contained Aisle C and the laboratory air space was measured using a multimeter (ADM-850L). Air temperatures were gathered using multiple sensor types. Discrete SynapSense™ temperature sensors, distributed as shown in Figure 1 (c) where they marked by red circles, were used to record air temperature in Aisle C. They were located at the inlets to the IT servers with a measured uncertainty of ±0.5 °F 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 and procedure

During all tests, the IT servers were exercised at 100% CPU utilization through the Linux operating system, resulting in a total IT power consumption of 88 kW. The cooling unit supply air temperature set point was 59 °F (15 °C). The cooling unit blower speed was adjusted via the variable frequency drive to maintain a neutral or slightly positive pressure differential in Aisle C when compared to the rest of the laboratory space (0 - 0.002" of H_2O). 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 CRAH blower was deliberately failed 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 A1 servers of 32 °C, after which the cooling unit blower power 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 without pressure relief (CAC doors are kept closed). The second was introducing pressure relief by opening the containment doors after 5 minutes of cooling failure and closing the doors 5 minutes after recovery took place to simulate the need of doors opening/closing.

Table 2 below provides details for the test procedure of both scenarios in time. In both cases, the steady state conditions were reached before data collection was initiated at time zero. Cooling failure is introduced at 10 ± 1.5 minutes. The system took time to reach the second steady state after recovery for the case of no pressure relief. Note that the different DC components (CRAH, IT inlets, CPUs, etc.) need different time durations to reach the second steady state, which is dictated by location, stored thermal energy, and proximity to the cold air stream.

Table 2. Experimental Tests Procedure Timetable [Min.].

Description	First scenario	Second scenario
Start data collection	0	0
Introduce Cooling failure	10	10
Open CAC doors	No action	15
Restore blowers	56	35
Close CAC doors	No action	40
End Test and data collection	120	120

Results and Discussion

Pressure Differential

This section focuses on analyzing the pressure differential data across Aisle C for the two test scenarios, with and without pressure relief. The data is presented in Figure 2. The figure shows that both tests start with a neutral pressure differential in Aisle C. Once failure occurs, it generates a negative pressure differential across the CAC, which indicates that it's under-provisioned. In the second test with pressure relief, once the containment doors are opened, the differential pressure jumps to zero and the IT equipment are now drawing air from all possible paths in the room, with very minimal air from the plenum. In the first test, without pressure relief, the differential pressure across the CAC continues to decrease with time as IT fans modulate from idling (low) to high (maximum) RPM. The generated negative pressure drives air from the room into the aisle through leaks in the containment, but the majority of air enters the aisle from the underfloor plenum.

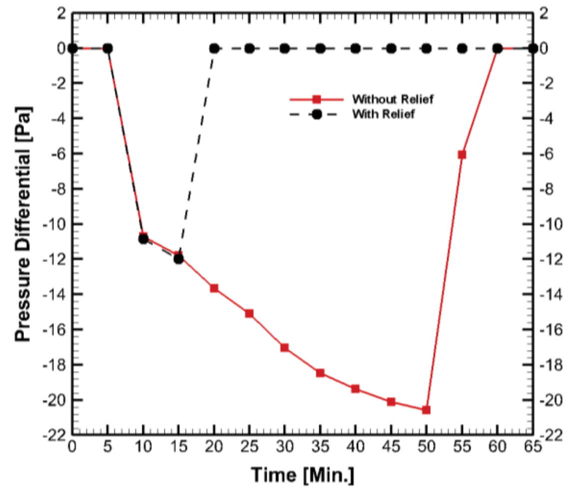


Figure 2. CAC Pressure Differential.

Critical Servers and IPMI Response

This section will focus 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 242 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 2950-118) located in the middle of the rack C1-8 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 C2-7 (server R520-01) 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) shows the behavior of the inlet temperature as reported by the IPMI protocol of the critical servers (d2950-118, R520-01 and C2100-01) with and without pressure relief. It can be noted that the value and gradients of the IPMI inlet temperature for the d2950-118 without pressure relief are always higher than those for the same server with pressure relief, where the maximum reported values are 32℃ and 42℃ for with and without pressure relief respectively. 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 is the result of a single power supply installed in the server. The empty power supply bay allows a recirculation path when the existing power supply fan is inadequate to overcome the external resistance of the CAC when a cooling failure event takes place (10 Pa at low RPM and 22 Pa at high RPM). The change in pressure results from the server fans accelerating between low and high temperatures so the reduction in airflow rate decreases as discussed in [22, 27]. Furthermore, by comparing the IPMI data of the d2950-118 with and without pressure relief, it can be noted that the curves start to deviate at the point where the pressure is relieved, which indicates a correlation with the induced back pressure. The other two models of servers (R520 and C2100) have minimal differences in temperature data with and without pressure relief. The internal design differences between the server models directly impact how they respond to increased external resistance. On examining the IPMI inlet temperature for the d2950 with no pressure relief, it appears that fewer IT equipment are available during the cooling failure and RTT. However, contrasting results are seen for these same parameters when discrete sensors and reported CPU temperatures are used.

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, the IPMI inlet temperature goes up faster without pressure relief than with pressure relief present. If the inlet air temperature to the server was elevated, then it would be expected that the CPU temperature would be higher without pressure relief. However, the opposite trend occurred for the average CPU temperature, as shown in Figure 3 (b). The figure shows that the CPU temperature goes up faster (steeper gradient) with pressure relief despite the lower IPMI inlet temperature. In addition, the figure indicates that without pressure relief it takes a longer time for the CPU to reach 95℃ for d2950. From this analysis, it is concluded that only the IPMI temperature sensor is affected by the internal recirculation and that the CPU temperature is not significantly impacted.

Figure 3 (c) shows the server fan speed behavior for all types of servers in Aisle C with and without pressure relief. As cooling failure takes place, the server's fans start to accelerate to compensate for the temperature increase. The figure indicates that without pressure relief the d2950 servers' fans ramp up faster than with pressure relief present, which was not the case for the other two classes of servers. This is most likely due to differences in the fan algorithm used for each model of server. From previous work [26], it is known that the d2950 fans are controlled based on the IPMI inlet temperature sensor.

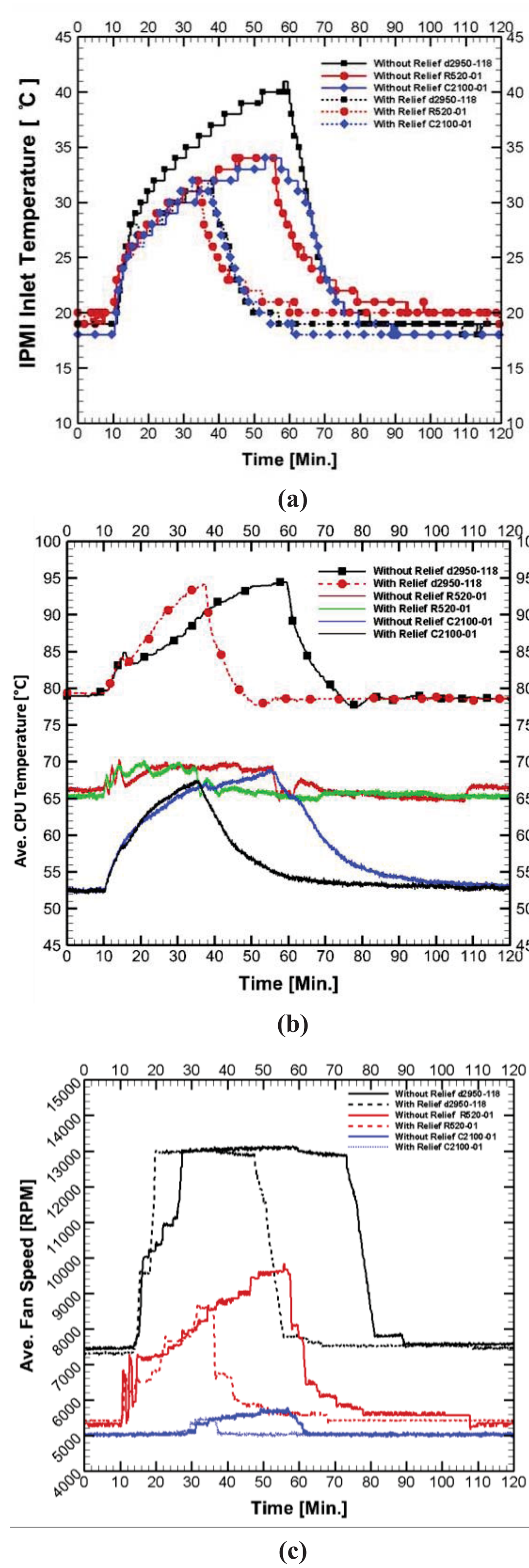
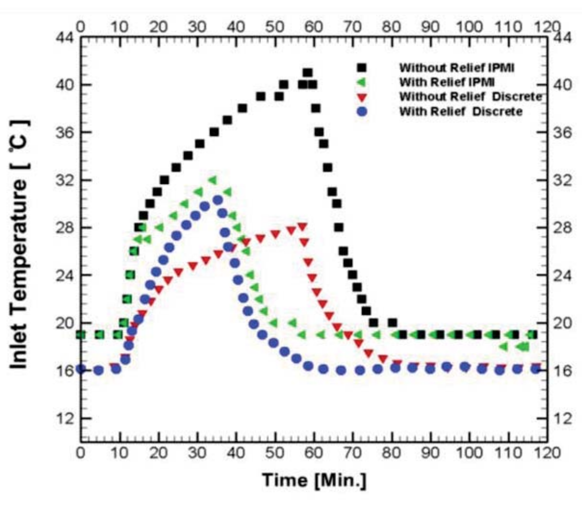


Figure 3. (a) IPMI inlet temperature. (b) Ave. CPU temperature. (c) Server Ave. fan speed.

IPMI vs Discrete Inlet Temperature 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 with and without pressure relief for the d2950-118 server, R520-1 server, and C2100-01 server, respectively. The discrete inlet temperature data exhibited the same behavior for all three server models. The data shows that keeping the aisle contained (no relief), kept the contained aisle cooler for an extended period after failure than in the case of opening the aisle doors (with relief). This is attributed to the 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, with the containment doors open, there is no negative pressure buildup inside the containment and the servers are now pulling air from the warm air in the room, causing the server inlet temperatures to rise quicker. Therefore, based on the discrete sensor data, keeping 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 R520-01 and C2100-01, figures 4 (b) and (c) respectively, the IPMI inlet temperature data were the same for with and without pressure relief. However, the IPMI inlet temperature data for the d2950 server in Figure 4 (a) shows that without pressure relief, the server inlet temperatures rise much faster than with pressure relief. Therefore, based on the IPMI inlet temperature data for the d2950 server, opening the containment doors during failure provides a longer RTT.



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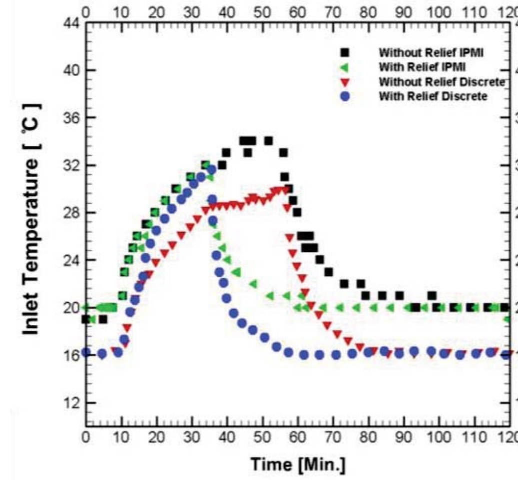

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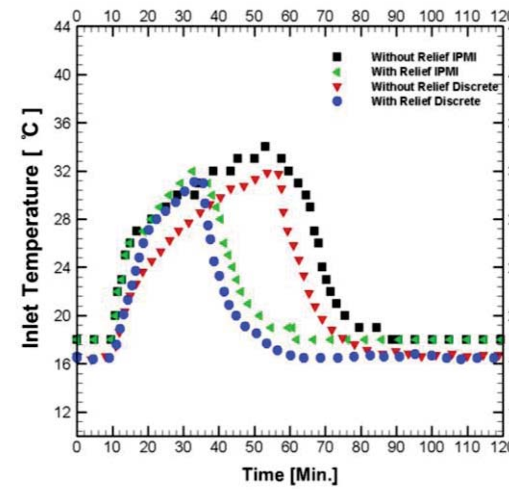

(c)

Figure 4. IPMI vs Discrete inlet temperature (a) d2950-118. (b) R520-01. (c) C2100-01.

Given the conflicting conclusions between the discrete and IPMI server inlet temperature data, the team focused on the temperature of one of the major components inside the server, and that is the CPU. As discussed in the previous section, the average CPU temperature data for the d2950 server presented in Figure 3(b) shows that without pressure relief, the increase in CPU temperature was much slower during failure when compared to the case with pressure relief. This shows that the CPU temperature follows the same trend as the discrete sensor data, indicating that keeping the aisle contained in the case of failure will provide a longer RTT.

Cooling Infrastructure Response

As explained in the previous sections, keeping the cold aisle contained during cooling failure was beneficial to the servers because they could draw air from the underfloor plenum. To further analyze, Figure 5 compares the cooling unit SAT over time for both cases tested. The cooling unit SAT starts to decrease in both cases when the cooling unit failure occurs. Once the doors are opened in the pressure relief test case, the SAT jumps up to about 58℉ and remains constant until the cooling unit is switched back on, where it makes another jump to about 65℉. However, in the no pressure relief test case, the SAT continues to decrease to about 56℃. The SAT remains at 56℃ for some time and starts to rise gradually with time until the cooling unit power is restored. The behavior of the SAT in the no pressure relief case indicates there is airflow across the cooling unit, which is driven by the IT equipment. As the heat builds up in the room, the RAT rises gradually and thereby the SAT rises due to the airflow across the cooling unit. Therefore, not only are the servers pulling the cold air from the plenum during failure, they are also taking advantage of the inherent cooling storage capability of the cooling unit due to the thermal mass of its various components (heat-exchanger coils, cold water, etc.)

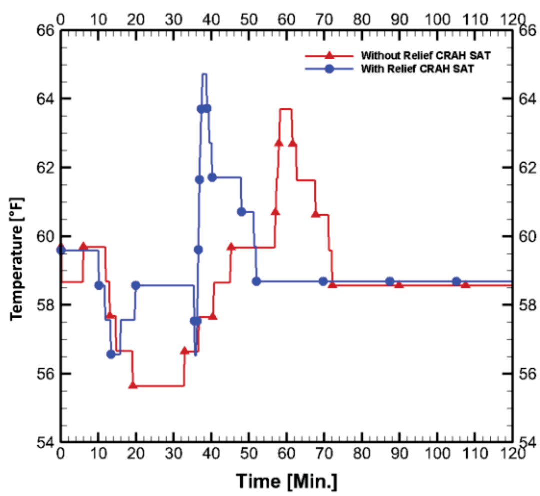

Figure 5. Cooling unit SAT data.

Uptime Analysis

Tables 3 and 4 present a comparison of the estimated uptime (RTT) without pressure relief and with pressure relief, 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 the IPMI inlet temperature sensors without pressure relief underestimate the RTT by ~ 32% (T_{A1} threshold) compared to the estimated RTT through the discrete monitoring sensor for C2100 server. In contrast, with pressure relief it underestimates the RTT only by ~ 8% compared to that estimated through discrete sensors.

Table 3. Ride Through Time without pressure relief Comparison [Min.].

Threshold	Ext. T_{in}			IPMI T_{in}		
	d2950	R520	C2100	d2950	R520	C2100
Failure – 27 °C	40	20	20	6	8	9
Failure – 32 °C	NR	NR	44	11	24	30

Table 4. Ride Through Time with pressure relief Comparison [Min.].

Threshold	Ext. T_{in}			IPMI T_{in}		
	d2950	R520	C2100	d2950	R520	C2100
Failure – 27 °C	14	12	9	8	8	9
Failure – 32 °C	NR	NR	26	26	24	24

Conclusions

This study presented an experimental based analysis on the ride through time (RTT) of servers inside containment during blower failure. Two scenarios were tested to understand the effect of cold aisle containment (CAC) during failure. In the first scenario, the containment doors were kept closed, representing a no pressure relief case. In the second scenario, the containment doors were opened five minutes into the blower failure, representing a pressure relief case.

The results showed that for all three classes of servers tested, pressure relief is not required. On the contrary, during blower 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. The data further showed that the servers could pull air from plenum through the cooling unit, taking advantage of the inherent cooling storage capability of the cooling unit, which was due to the thermal mass of its various components (heat-exchanger coils, cold water, etc.), thus providing a longer RTT.

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