Experimental Description of Information Technology Equipment Reliability Exposed to a Data Center Using Airside Economizer Operating in Recommended and Allowable ASHRAE Envelopes in an ANSI/ISA Classified G2 Environment

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Airside economizers lower the operating cost of data centers by reducing or eliminating mechanical cooling. It, however, increases the risk of reliability degradation of information technology (IT) equipment due to contaminants. IT Equipment manufacturers have tested equipment performance and guarantee the reliability of their equipment in environments within ISA 71.04-2013 severity level G1 and the ASHRAE recommended temperature-relative humidity (RH) envelope. IT Equipment manufacturers require data center operators to meet all the specified conditions consistently before fulfilling warranty on equipment failure. To determine the reliability of electronic hardware in higher severity conditions, field data obtained from real data centers are required. In this study, a corrosion classification coupon experiment as per ISA 71.04-2013 was performed to determine the severity level of a research data center (RDC) located in an industrial area of hot and humid Dallas. The temperature-RH excursions were analyzed based on time series and weather data bin analysis using trend data for the duration of operation. After some period, a failure was recorded on two power distribution units (PDUs) located in the hot aisle. The damaged hardware and other hardware were evaluated, and cumulative corrosion damage study was carried out. The hypothetical estimation of the end of life of components is provided to determine free air-cooling hours for the site. There was no failure of even a single server operated with fresh air-cooling shows that using evaporative/free air cooling is not detrimental to IT equipment reliability. This study, however, must be repeated in other geographical locations to determine if the contamination effect is location dependent. [DOI: 10.1115/1.4046556]

Introduction

Information technology (IT) equipment manufacturers are now becoming increasingly aware of the risk of contamination on their products. Their products are now tagged with information that clearly indicates the environmental limits for safe operation. Nowadays, data center administrators/operators must demonstrate the operation of their equipment within the acceptable environment before warranty claims can be fulfilled [1,2]. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) TC9.9 committee has specified certain recommended and allowable envelopes for a data center operation in Refs. [2–6].

The psychrometric chart in Fig. 1 illustrates the recommended and allowable ranges for temperature and humidity, respectively [2–6]. Air entering the data center through airside economizers operating outside ASHRAE's recommended temperature–humidity envelope is a potential risk to IT equipment within the data center [6]. Environmental factors such as temperature, relative humidity, and gaseous and particulate contaminants can cause printed circuit boards (PCBs) to fail in two major ways:

- Electrical open circuits occurring due to corrosion, for instance corrosion of silver terminations in surface mount segments, surface mount resistors endure open circuits because of the consumption of their silver terminations by sulfur bearing gaseous contaminants in polluted geographies [2,3,7–10].

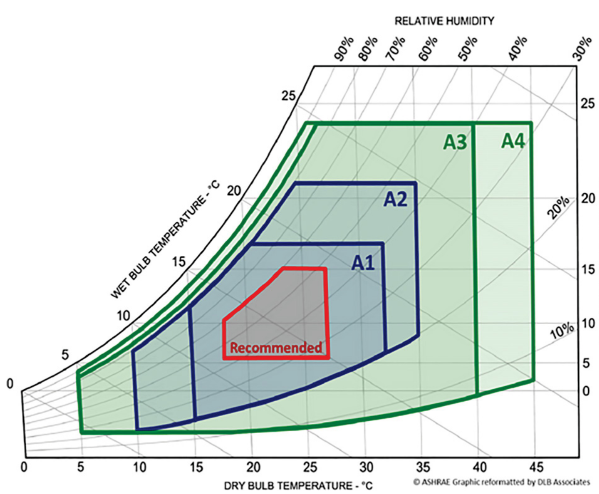

Fig. 1 ASHRAE psychrometric chart showing the IT equipment manufacturer recommended and the allowable ranges: recommended range: temperature—18 °C to 27 °C, RH—60%; allowable range: A1: 15 °C to 32 °C, RH—8% to 80%; allowable range: A2: 10 °C to 35 °C, RH—8% to 80%; allowable range: A3: 5 °C to 40 °C, RH—8% to 85%; and allowable range: A4: 5 °C to 45 °C, RH—8% to 90%

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Table 1 Gaseous corrosivity levels as per ANSI-ISA-71.04-2013

Class	Severity level	Copper reactivity (Å)	Silver reactivity (Å)	Comments
G1	Mild	<300	<200	Corrosion is not a factor in determining equipment reliability
G2	Moderate	<1000	<1000	Corrosion effects are measurable, and corrosion may not be a factor electroless nickel immersion gold and ImmAg surface finish failures
G3	Harsh	<2000	<2000	High probability that corrosive attack will occur. Organic solderability preservative and ImSn PCB surface finish failures
GX	Severe	>=2000	>=2000	Only specially designed and packaged equipment to survive

- Electrical short circuiting due to copper creep corrosion, by electrochemical reactions such as ion migration and cathodic–anodic filamentation [2,3,10–14]

Corrosion of IT equipment is the reaction between certain metallic parts (specifically copper and silver) and the surrounding environment, which causes deterioration of the parts. The corrosion rate is known to accelerate with an increase in temperature and relative humidity.

The composition of the contaminants in the air determines the corrosivity of the environment. Determination of this composition is not a trivial task. A guide for specifying data center environmental severity level has been published by ANSI/ISA-71.04-1985. The environmental classification limits adopted by ANSI/ISA uses a method called "reactive monitoring" to quantify and classify the severity level of the environment because of gaseous contamination [15,16]. In reactive monitoring, analysis of corrosion product thickness and chemistry is performed on copper coupons, exposed to the environment for a 1-month period. Similarly, an analysis on silver coupons is conducted to study environmental chemistry of sulfur-bearing gases. Gaseous corrosion severity levels as per ANSI/ISA-71.04-2013 are described in Table 1 [15,16].

This paper serves multiple purposes including determination of the severity level of the research data center (RDC) site as per ANSI/ISA 71.04-2013 and providing the end of life of IT equipment operating at a harsh environment in a real-world data center. The experiments were conducted in two parts: the first was to evaluate the environment severity of the experimental data center using the procedures specified in ANSI/ISA-71.04-2013 [15–17] with both silver and copper coupons. The second experiment was a continuous operation of the data center until a failure of any of the electronic hardware was reported.

Knowing the limits of operation of certain IT equipment hardware is helpful in providing IT equipment manufacturers with some information that might encourage them to make their equipment more robust to perform reliably even beyond the recommended environmental severity level. Based on the literature review, there are several reported laboratory and field experiments to understand the impact of corrosive environment on IT hardware [3]. These experiments have either been performed to understand the corrosion rate of an environment or to establish the mode of failure. Others have been too focused on the measurement techniques. This paper addresses such experiments in a real-world data center especially in a G2 class environment.

Research Data Center Site Description

The research data center utilized in this study is a modular data center situated in the Dallas industrial area which is polluted due to surrounding manufacturing activities. The facility utilizes an airside economizer with direct and indirect evaporative cooling (IEC) for the thermal management. It has four racks with IT hardware like servers, power distribution units (PDUs), UPS systems, and storage devices. Figures 2 and 3 show different components of the RDC, such as the IT pod and the cooling unit (which consists of the cold air supply duct, hot air exhaust/return duct, mixing chamber, and I/DEC cooling unit). The size of the research modular data center is 10 ft × 12 ft × 28 ft (width × height × length) [18].

Information Technology Pod Configuration. The IT pod represents a cold aisle and hot aisle arrangement with four server racks, PDUs, UPS and workstation. Air enters through the supply duct into the cold aisle across the cabinet to cool the servers, then transferred into the hot aisle from where it returns through the return duct.

- *Size*: 126 in. × 85.5 in.
- *IT equipment*: HP SE1120 Servers (120 Servers)
- *Cabinet*: S6212B PANDUIT Rack
- *Flow provisioning*: End inlet and outlet configuration
- *Inlet dimensions*: 13 × 27 vent with 45 deg Louver angle
- *Outlet dimensions*: 13 × 27 vent [18]

The cooling unit is an air-side economizer with direct and indirect evaporative cooling. The data center uses free air cooling in suitable environmental conditions and uses direct cooling and/or indirect cooling and/or return air and/or mixing of return air with outside air to achieve ASHRAE recommended operating conditions in the cold aisle when the environmental conditions are extreme [18–20].

Physical Environment: Temperature and Relative Humidity. Over the course of the experiments, temperature and relative humidity readings were taken in cold and hot aisles. The physical environmental conditions of the IT pod were classified in the different regions of psychrometric chart and summarized below. The regions in Figs. 4 and 5 show recommended and Class A1 allowable regions of the cooling units (ASC-15-2A11) to bring outside air into the target regions. These regions help in determining if it is feasible to operate the ASC-15-2A11 cooling unit to bring outside air. For both charts, the cooling unit cannot be used if the outside air conditions lay in Region 1, since it represents excessive moisture in air to be used for the target regions. It, thus, necessitates the use of Dehumidifiers, DX cooling units, or multistage IEC units. The values of environmental parameters in this region can be directly obtained from the psychrometric chart itself. For all other regions, except region 1, the cooling unit can be used to bring outside air into the target regions as they represent favorable environmental conditions for IT equipment cooling. The use of

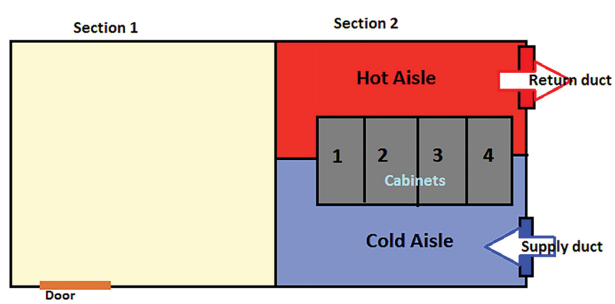


Fig. 2 Experimental IT pod showing the cold and hot aisles

Fig. 3 Cooling unit and IT pod of the modular data center

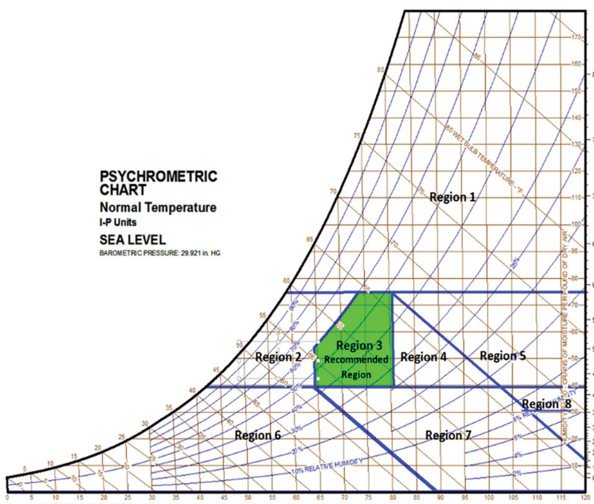


Fig. 4 Psychrometric chart regions based on the recommended envelope

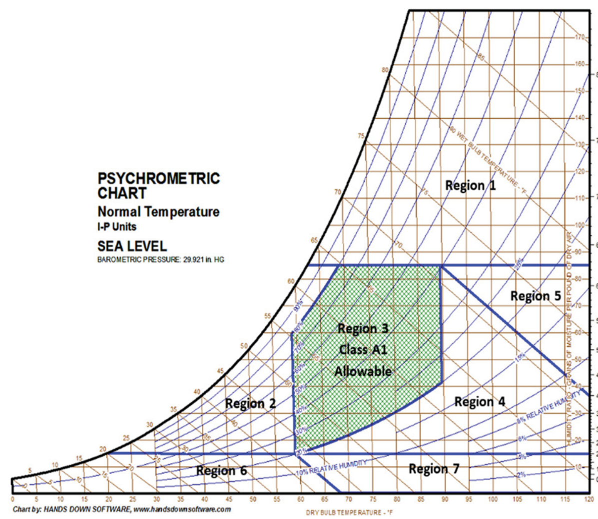


Fig. 5 Psychrometric chart regions based on class A1 allowable region

DEC, IEC, and I/DEC is based on keeping the dew point, dry bulb temperature, or wet bulb temperature within the ASHRAE recommended and allowable temperature limits of the supply air. Below is a summary of how this may be achieved if outside air falls in:

- Region 2: The cooling unit mixes hot return air with outside air.
- Region 3: Directly takes outside air.
- Region 4: Based on the recommended envelope either DEC or IEC can be used. However, according to the Class A1 allowable envelope, only DEC is guaranteed to work for this region. I/DEC mode can be used for more efficient results.
- Region 5: Use of IEC is must; I/DEC can be used for more efficient results.
- Region 6: mix hot return air with outside air. It may be necessary to run the DEC section to add moisture.
- Region 7: Must use DEC, additionally I/DEC can be used for more efficient results.
- Region 8: Both IEC and DEC must be used [18–20].

Various scenarios summarized above are the guidelines for operating the RDC. This was plotted on psychrometric charts overlaid with ASHRAE recommended and allowable regions as shown in Figs. 4 and 5.

Particulate Contamination. The filtration of particulates should be as outlined here:

(1) Continuously filter room air with MERV 8 filters as recommended by ANSI/ASHRAE Standard 127-2007, “Method of Testing for Rating Computer and Data Processing Room Unitary Air Conditioners” (ASHRAE 2007)
(2) Filter air entering data center with MERV 11 or MERV 13 filters as recommended by the ASHRAE book with the title “Particulate and Gaseous Contamination in Datacom Environments” (ASHRAE 2014) [1–3]

In this research data center, MERV 11 rating filter was installed to filter off particulates that might flow in with the outside air and enter the mixing chamber from the ambient. Table 2 illustrates the

Table 2 Particulate matter and their sources

Contaminant	Source
Zink whiskers	Zinc coated information and communication equipment, steel building studs
Tin whiskers	Components and products having electroplated tin
Oxide flake off	Magnetic media
Natural and artificial fibers	Paper, cardboard, etc.
Water soluble ionic salt	Chemical reactions
Sulfates, nitrate, sea salts	Winds
Lime dust with water	Concrete material
Dust	Farm, especially during plowing
Toner dust	Toner
Smoke	Cigarette, winds
Cellulose fragments	Traditional ceiling tiles and spaces
Synthetic rubbers	Belt drive and pully

types and sources of particulate materials generally found in the industrial area, where the RDC is sited [19,20]. An important aspect of particulate contamination to look out for is its deliquescent relative humidity, whereby dust and/or salts of gaseous contaminants can absorb moisture, form an aqueous solution on PCB surface, and in turn cause corrosion and/or ion migration in adjacent components or copper/silver connections, thus, degrading the IT parts.

Gaseous Contamination. As per ANSI/ISA-71.04-1985, gaseous contamination should be within the severity level G1 which meets the following criteria:

(1) Copper reactivity rate of less than 300 Å/month
(2) Silver reactivity rate of less than 200 Å/month [15,16]

For data centers that do not meet the above-mentioned criteria for copper and silver corrosion rates, gas-phase filtration is recommended to prevent gaseous contaminants from entering the data center. The restriction of hazardous substances directive banned the use of Lead in the circuit boards, which led to the use of silver as the soldering material. These circuit boards are highly susceptible to corrosion due to gaseous contaminants. Some of the common gaseous contaminants are sulfur dioxide (SO_2) and hydrogen sulfide (H_2S);b with other gases such as nitrogen dioxide (NO_2), chlorine, and ozone (O_3) also playing an active role in the corrosion of IT equipment. The experiment was carried out to determine the severity level of the research data center facility as per ANSI/ISA 71.04-1985 using the corrosion classification coupons.

Coupon Testing Experiment to Measure the Severity Level of Research Data Center

Testing was conducted in the experimental data center located in polluted geographies to measure the severity level.

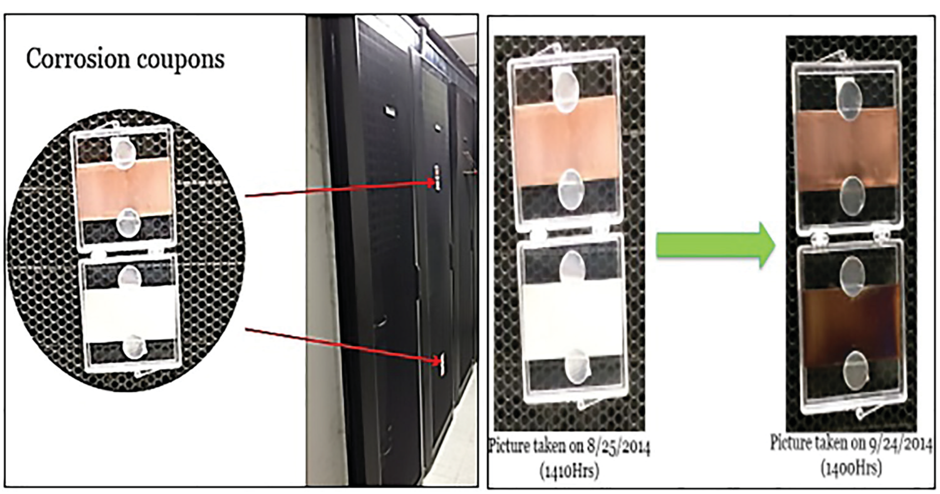
Corrosion rates should be determined in two ways:

(1) Exposing metal coupons (CCC) for a 30-days period and determining the corrosion product thickness via coulometric reduction.
(2) Exposing thin metal films and tracking the real-time corrosion rates by measuring the resistance change of the films. The corrosion rates should be measured at predetermined temperatures and humidity ranging from 20 °C to 50 °C and 30 to 90% relative humidity (RH).

For this experiment, copper and silver coupons were placed in front of the rack, as shown in Fig. 6(*a*), at $1/4$ and $3/4$ heights to check the corrosion severity level. The coupons were placed facing the incoming air into the rack and were also adjusted slightly for adequate airflow impact while entering the rack. Any dead airflow spots were avoided. The coupons were left exposed for a period of 1 month after which the corrosion product thickness was determined via coulometric reduction [19,20].

Results and Discussion

Coupon Experiment Results. For the coupon experiment, after 30 days of exposure, the coupons were retrieved and analyzed using coulometric reduction. This technique utilizes the fact that different corrosion products will be reduced at different potentials. A plot of reduction potential of different corrosion products versus time to reduce to respective compounds is then plotted to describe the compounds formed. A standard formula, as described in ASTM B825 is then used to calculate the mass of the corrosion products formed and film thickness of the corrosion product on the corrosion coupon [21]. Figure 6(*b*) shows the state of the coupons before and after 30 days of exposure. The corrosion rate was calculated by Coulometric Reduction Method at S&T Group Materials Laboratory by IBM (STSM, Metallurgical and Materials Engineering and Microelectronic Manufacturing, Poughkeepsie, NY).



(*a*) (*b*)

Fig. 6 (*a*) Coupon location at the cold aisle section of modular data center and (*b*) copper and silver coupons before and after the 30 days exposure

Table 3 Coulometric results of the corrosion thickness on both copper and silver coupons

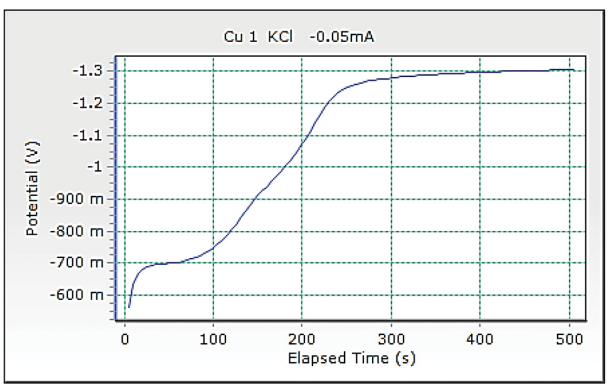
Coupon	Copper corrosion product	Seconds	Thickness of corrosion product, angstroms	Exposure days	Copper corrosion rate, angstroms/month
1	Cu_2O	98	68	30	102
	CuO	94	34		
	Cu_2S	0	0		
2	Cu_2O	133	92	30	122
	CuO	83	30		
	Cu_2S	0	0		
Coupon	**Silver corrosion product**	**Seconds**	**Thickness of corrosion product, angstroms**	**Exposure days**	**Silver corrosion rate, angstroms/month**
1	Ag_2S	373	363	30	363
2	Ag_2S	240	233	30	233

Details of the corrosion products from the coulometric evaluation are described in Table 3. Copper coupons 1 and 2, as shown in Table 3, disclosed the thickness of corrosion products only for Cu_2O, CuO; and none for Cu_2S, while for corrosion thickness of products of Silver, only Ag_2S was found on both coupons. The interest of this paper is to establish the environmental class from the amount of corrosion thickness in Angstrom during the period of exposure. On both silver coupons, the corrosion thickness exceeds the G1 severity zone. This suggests that for the month, based on this information, the data center environment can be classified as an ISA 71.04-2013 G2 severity level.

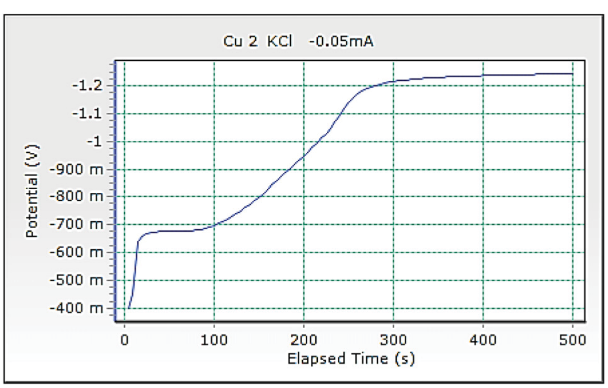
Industrial activities around the area have higher Sulfur content in the atmosphere as you will normally not see in the U.S. or the environs. This provides an opportunity to have a potential environment beyond G1, although there is currently no data to suggest that the same environment is possible all year around. Figures 7 and 8 describe the potential readings in volts with the elapsed time in seconds.

In Figs. 7(*a*) and 7(*b*), the plateau at about 600 mV is due to the reduction of Cu_2O oxide to Cu metal. The other plateaus at 800 mV for CuO and at 1050 mV for Cu_2S are not as dominant as Cu_2O plateau is. This means that Cu_2O is the dominant corrosion product on the copper foil. In Figs. 8(*a*) and 8(*b*), there are two plateaus: One at 820 mV for the reduction of Ag_2S to Ag. The other plateau at about 1250 mV is not associated with the reduction of any corrosion product. The dominant corrosion product on Ag is Ag_2S.

Weather Bin Data Analysis on Psychrometric Chart Regions Based on Trend Data of Research Data Center. The bin data in Fig. 9 show average inlet conditions for the month of April 2015 at the cold aisle. The data are collected from the temperature–humidity monitoring sensors placed at the cold aisle

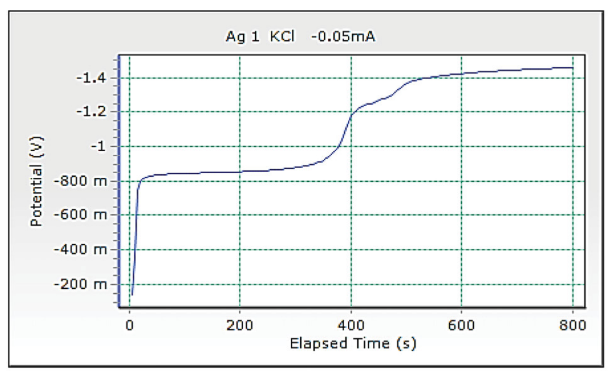


(*a*)



(*b*)

Fig. 7 (*a*) Plot of coulometric/cathodic reduction for copper coupon-1 and (*b*) plot of coulometric/cathodic reduction for copper coupon-2



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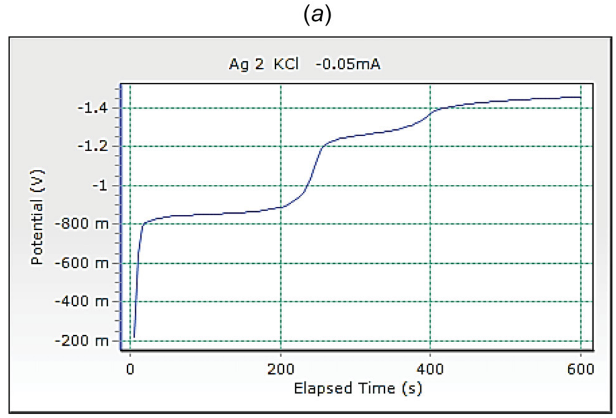

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Fig. 8 (*a*) Plot of coulometric/cathodic reduction for silver coupon-1 and (*b*) plot of coulometric/cathodic reduction for silver coupon-2

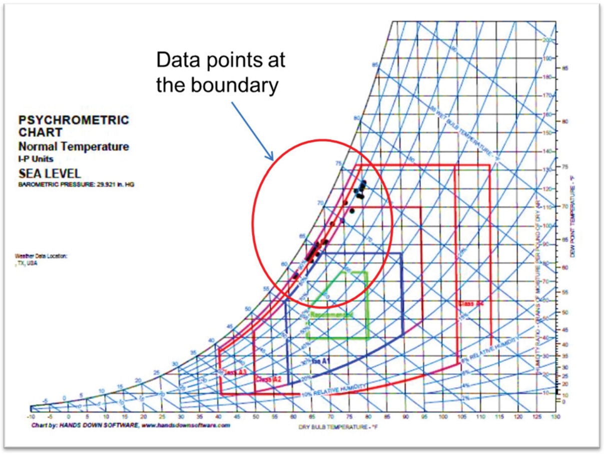


Fig. 9 Bin data showing average inlet conditions for the month of April 2015 showing equipment exposed to A2 and A3 envelopes

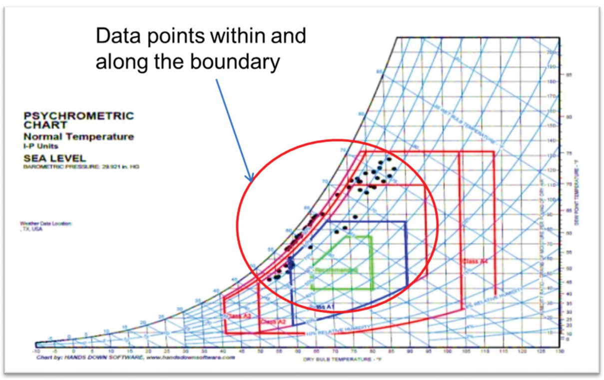


Fig. 10 Bin data for the month of May 2015 showing most of the obtained data points at the boundary of A3 and A4 allowable envelopes

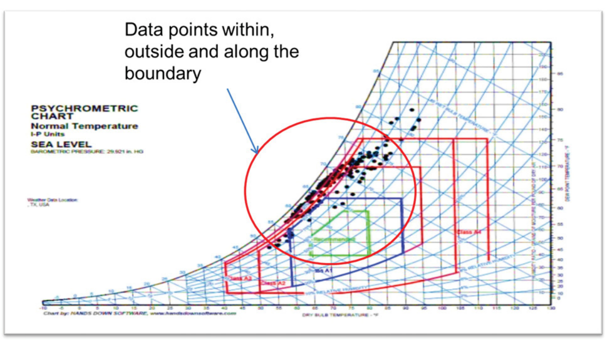


Fig. 11 Bin data showing average inlet conditions for the month of June 2015 with more excursions outside the recommended regions

and right after the supply duct for an interval of every 15 min during the operation. The temperature and humidity data obtained from these sensors were averaged for each day for a month. These average values of the environmental conditions were then superimposed on the psychrometric charts. The data were collected for the entire investigation time of the study, but to keep the paper concise, data for months of April, May, June, and July are reported. The environmental data within the circle, as plotted on

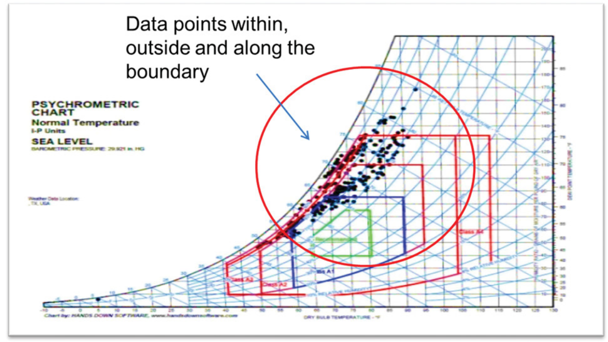
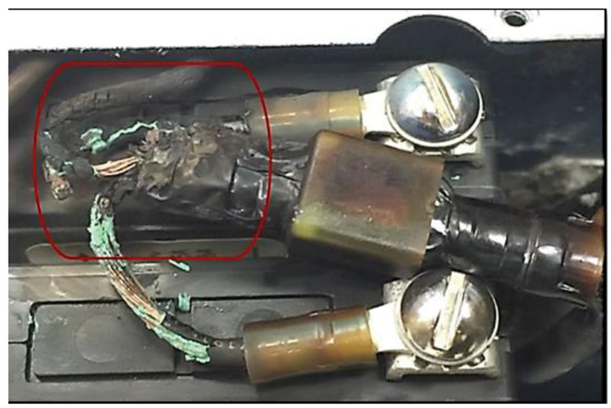


Fig. 12 Bin data showing average inlet conditions for the month of July 2015 showing higher ambient conditions within the data center

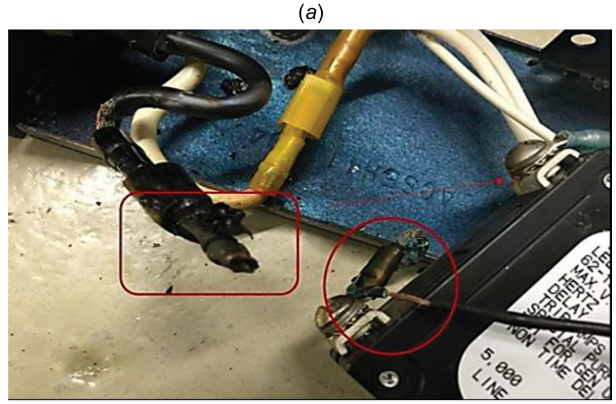
the psychrometric chart with dry and wet bulb temperatures, are mostly in the A3 allowable region from ASHRAE TC 9.9 guidelines. It is an indication that our IT equipment was exposed during this period to conditions well outside the recommended zone. In allowable A3, you have an upper dry bulb temperature of 40 °C.

For the month of May, as shown in Fig. 10, there is some distribution of inlet conditions across A2–A3. Here, some data points are in the A1 region, but none are in the recommended envelope. There are slight excursions into A4 zone as well.

In the month of June, as shown in Fig. 11 along with the distribution across A1–A4, there were excursions well outside both the recommended and the allowable zones. Although the percentage excursions outside the allowable zone are less than 10% in this

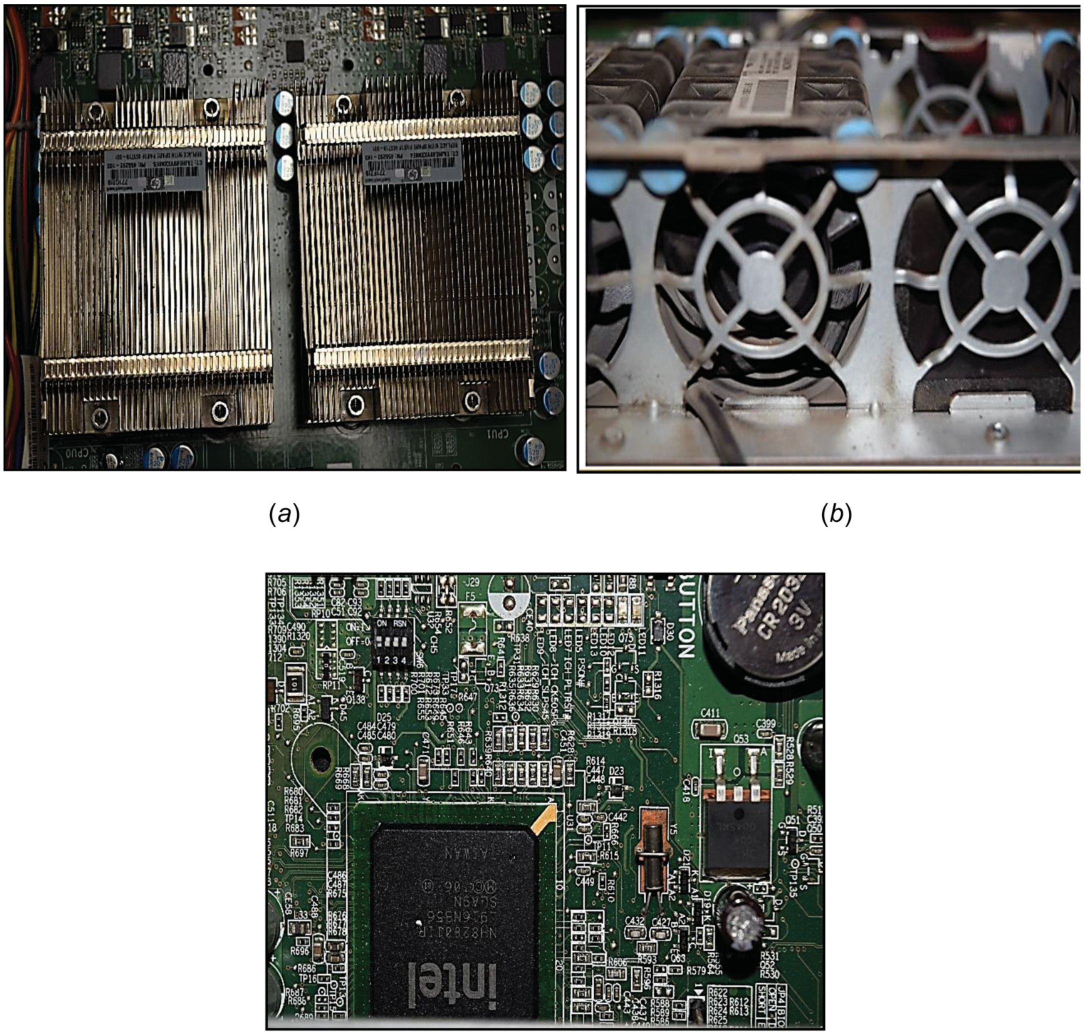


(*a*)



(*b*)

Fig. 13 (*a*) Failed PDU-1 in hot aisle and (*b*) failed PDU-2 in hot aisle



(*a*) (*b*)

(*c*)

Fig. 14 (*a*) Lodged dust on heat sinks, (*b*) accumulated dust on fans, and (*c*) dust on printed circuit boards

Table 4 Total hours of operation of an airside economizer with direct and indirect evaporative cooling during different months of years 2014 and 2015, respectively

	No. of hours of operation	
Month	Hours	Minutes
May, 2014	38	14
June, 2014	337	11
July, 2014	282	47
August, 2014	71	20
September, 2014	84	31
October, 2014	569	1
November, 2014	596	20
December, 2014	93	20
April, 2015	329	22
May, 2015	549	57
June, 2015	611	47
July, 2015	626	18
August, 2015	563	23
September, 2015	600	30
October, 2015	613	10
November, 2015	265	4
Total	6232	15

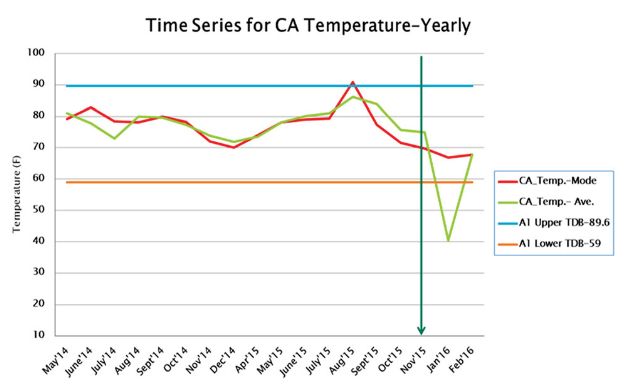


Fig. 15 Time series for cold aisle temperature (yearly) showing the first reported failure after 3622 economizer hours

case, the IT equipment is not rated for such environments. It might have negative implications for failed hardware.

In the month of July, as shown in Fig. 12, the excursions outside the recommended/allowable envelope are almost the same as the month of June and they have similar distributions.

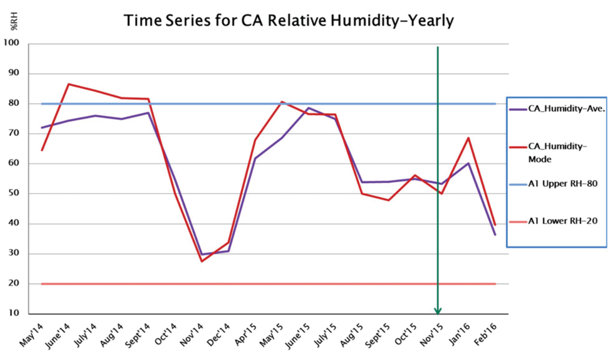


Fig. 16 Time series for cold aisle relative humidity (yearly) showing the first reported failure indicated by the green arrow

Discussion on a Power Distribution Unit Failure. The research data center was under operation until a failure was recorded on two PDUs in the hot aisle adjacent to the racks. Figures 13(*a*) and 13(*b*) show failed PDUs in the hot aisle. Copper connectors as seen appear to have been exposed directly to the surrounding air with the right temperature and moisture and certain levels of contaminants. As we can see from the picture, the insulator appears burnt exposing the cables to the atmosphere. Rust on the steel screw due to moisture was observed. The oxide formed on the connector after the short circuit was also found. This indicates a possibility of condensation in the hot aisle. The higher moisture content might have caused condensation on the chassis and on the surface of power supply components. There was a rapid change in outside air conditions, as inferred from the trend data and actions of direct evaporative cooling unit toward humidity variations. However, there are seven PDUs, out of which only two failed after a long period of operation.

Qualitative Observation of Servers. In addition, the following hardware components shown in Figs. 14(*a*)–14(*c*), respectively, are of the server under operation in the research data center, visually inspected for possible gaseous/particulate contaminants:

(1) heat sinks,
(2) server fans, and
(3) printed circuit boards.

No significant degradation due to corrosion was observed on the above components other than pockets of dust around the server fans and heat sinks as shown in the figures [22]. This is attributed to the quality of installed MERV 11 particulate contaminant filter in the data center. It is extremely difficult to filter out the fine dust particles with filters of this efficiency [23].

Conclusion

Table 4 shows total number of hours of operation of an airside economizer with direct and indirect evaporative cooling during different months of years 2014 and 2015, respectively, (The PDUs failed in Nov.'15) at the Research Data Center. As per Table 4, by Nov.'15 when the first PDU failure was reported, the data center cooling unit completed the operation of 6232.25 h for free air cooling with direct and indirect evaporative cooling. Out of 6232.25 h of total operation for airside economization with direct and indirect evaporative cooling, 3622 h were for free air cooling, which is way higher than the recommended number of hours for free air cooling in Dallas. Based on the results of the above experiments, it is quite possible that air and moisture contributed to the failure of the PDUs. Two out of seven PDUs failed after 6232.25 h of operation. Failure is not due to corrosion. The visual inspection of different components after 6232.25 h of operation and temperature–relative humidity excursions outside the ASHRAE recommended envelope showed that no failure has occurred to IT equipment, especially servers susceptible to corrosion or expected to fail under such harsh conditions. No surface mount resistor failure was reported. This effort is still ongoing, as the intent is to run until failure and thereafter evaluate and understand the contribution of corrosion on the reliability of hardware in this environment.

Figures 15 and 16 demonstrate the time series of cold aisle temperature and relative humidity on yearly basis for the last 2 years, respectively, mentioning the first reported failure (2 PDUs failed) in Nov'15. The statistics are shown by using the mean (average) and mode (most occurring environments) values for each parameter monthly basis. The figures also show the lower and upper limits for allowable A1 dry bulb temperature (59–89.6 °F) and A1 relative humidity (20–80%), respectively. It can be inferred that the data center was operated in ASHRAE class A1 allowable (outside recommended) region for the maximum period during its tenure of the last 2 years. Coupon experiment also determines the severity level G2 for the research modular data center. However, no server failure was recorded.

Future Work

This is a continuous effort to characterize the corrosion impact on IT equipment reliability. Coupon testing will be continued every month to determine if the environment is G2 all year round. The other IT hardware examined for corrosion will be continuously monitored for potential failure. It is also required to understand the environmental excursions outside the ASHRAE envelope. Later, when G2 environment is fully characterized and its corrosion impact is understood, work is then expected to continue with a higher environment G3. Further work is planned on microscopic evaluation of any damaged IT to understand the prevailing corrosion type, i.e., due to particulate or gaseous.

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