THE EFFECTS OF TEMPERATURE AND RELATIVE HUMIDITY ON EXPOSURE OF LEGACY AND FUTURE TECHNOLOGY HARDWARE, UNDER REAL DATA CENTER CONDITIONS IN AN ANSI/ISA CLASSIFIED G2 ENVIRONMENT

by

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Abstract

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It is well established that it is safe to operate information technology (IT) equipment in a G1 classified contaminant severity level when operating within specified ASHRAE recommended and allowable limits in an air-side economizer data center. This is basis for which electronic equipment manufacturers provide warranty for their products. IT equipment manufacturers in the US now requires data centers operators to demonstrate that they meet all the specified conditions consistently before fulfilling warranty equipment failure. This places limitation to where data center utilizing air-side economizer can be located. In order to determine the reliability of electronic hardware in higher severity conditions field data obtained in real data center conditions are required.

A 30-day corrosion classification coupon experiments was carried out on an experimental data center jointly owned by EMNSPC and Mestex Industries located in an industrial area in Dallas. Results of the 30-day experiments working under the operating conditions with notable excursions outside the allowable ASHRAE envelope show a G2 contaminant severity level for that time of the year. Furthermore the data center was operated until a failure was recorded on one of the hardware installed. The damaged hardware and other hardware were evaluated and compared with same hardware operated in a G1 severity environment. This was determined to be a non-corrosion related failure that occurred after 3622 hours of operation on two power density units (PDU’s). Selected components within the data center were evaluated after 4320 hours. The evaluation did not reveal any corrosion degradation that might suggest, that their reliability was affected during the entire 4320 hours of data center operations/experiments in the classified G2 environment. These results suggest a timeline for the safe operation of ITE’s in a G2 classified environment.

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CHAPTER 1

Introduction

Data center is a facility that offers physical infrastructure for the computing, storage, and networking requirements of Information Technology (IT) services. Its operations cuts across almost all industries, like defense, oil and gas, health care, finances, government, entertainment and enterprise businesses and many more. This enterprise can be small, medium or large enterprises consisting of everything from a small e-mail server room to a large upscale industrial data center facility. The size of the facility can be from a small server room with a few kW to over 100MW in terms of energy requirement.

Fig 1 below shows the interior of a typical large-scale industrial data center with the following IT equipment:

1. Servers
2. Storage Equipment
3. Lightings
4. Communication Equipment
5. Power Distribution Units
6. UPS Systems
7. Cooling Systems

The data industry is rapidly growing as more and more demands on data usage increases in support of rapidly growing businesses requiring information technology (IT) services. This trend as witnessed in the rapid growth in cloud computing services by large corporations like Microsoft, Amazon, Apple, Google and Facebook.

Also increase in Internet usage created numerous business opportunities, but these services are supported by data center industry. This growth placed a huge demand on energy consumption.

In a study by (J.G Koomey 2005) one third of the total electricity used in data is dedicated to cooling the IT equipment’s i.e. computer room air conditioning (CRAC) systems. As demand in IT services increases and more electronic equipment are procured to meet the growing demand. The cooling load requirement of data centers also increases and associated electricity costs. This cooling load can be reduced by the introduction of outside air during suitable weather conditions (Sorell, 2007) into the data center to cool the electronic devices.

However there is a fear of increased higher failure rate of metallic components in the electronic manufacturing industry (Henry C et al) when outside air are introduced into the data centers for cooling. The metallic components have been identified as copper and or silver on circuit boards from effect of airborne contaminants (Lopez et al, Reid et al).

With this growing concerns in 2009 the IT American Society of Refrigeration and Air-Conditioning Engineers (ASHRAE) TC 9.9 published a white paper titled “Particulate and Gaseous Contamination for Data Centers,” With the intent to guide data centers located in areas with harmful environmental pollutants arising from admission of outside air into data centers.

Figure 1-1 Typical interior floor space of a large data center

Source: https://newsroom.fb.com/media-gallery/data-centers-2/lulea-facebook-data-center-interior

1.1. Data Center Energy Consumption and Increasing Growth Trends

In another study by (J.G Koomey 2011) assessing electricity usage between 2005 and 2010 for the US and the world. Data center accounts for about 2% of the total electricity used in the US in 2010 and 1.3% of all electricity use in the world. Globally, Google's data centers accounts for just under 0.01% of the world's electricity usage. This global electricity use annually can be generated by 70 to 90 large (500MW) coal-fired power plants.

Figure 1-2 below shows the predicted US electricity use for data centers from 2006 – 2010 if power consumption by data centers is not addressed.

In 2013, an estimated 91 billion kilowatt-hours of electricity was consumed by US data centers equivalent to 34 large (500-MW) coal fired power plants. It is also projected to increase to about 140 billion kilowatt-hours by 2020, equivalent annual output of 50 power plants.

Table 1-1 below summarizes estimated usage of data centers from natural resources defense council report (NRDC) for 2013 and 2020.

Year	End-Use Energy (B KWh)	Electricity Bills (US, $B)	Power Plants (500 MW)	CO2 (US) (million MT)
2013	91	9.0	34	97
2020	138	13.7	51	147
2013 -2020 Increase	47	4.7	17	50

Table 1-1; Estimated power and electricity bills in US for 2020

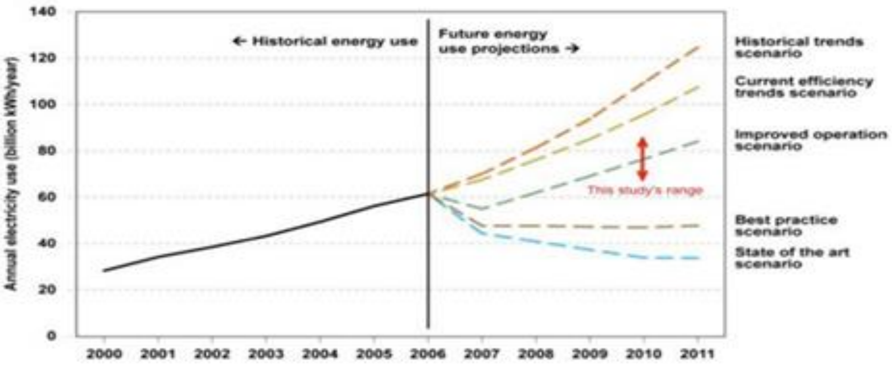


Figure ES-1: Predicted US electricity use for data centers from the EPA report to Congress (EPA 2007) and the range estimated in this study

Figure 1-2 Predicted US electricity use for data centers for 2006-2010 from EPA report

The growth trend from published work of ASHRAE TC 9.9 [4] shows increasing power density growth

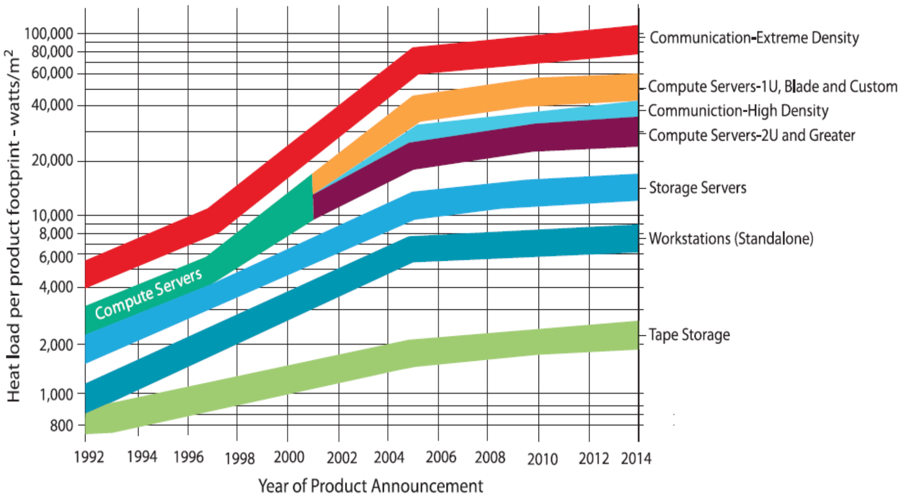


Figure 1-3; Growth trend from published work of ASHRAE TC 9.9 [4]

1.2. Power Usage Effectiveness of Data Center

This is a concept developed by the Green Grid and has now become the standard for measuring the power usage efficiency of a data center, PUE. This is the ratio between the total powers going into the data center facility to power consumed by the IT equipment.

$$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power} \quad (1\text{-}1)$$

The total facility power is power consumed by IT equipment and other supporting facilities (e.g. cooling, lighting etc.) If no power the ideal PUE is 1.0 but is impracticable meaning that there are no loses and no additional power was used for cooling. Average data center PUE in the US is about 2.0 [5] which means for every watt of power used by IT equipment there is a corresponding power usage by supporting infrastructures.

1.3. Data Center Energy use within the facility

A breakdown of energy consumption in a typical, 5000-square-foot data center (Figure 1-4) as analyzed by Emerson Network power report [6] and categorized as either "demand side" or "supply side". "Demand side systems are the IT equipment's like servers, storage, communications and other IT systems that support the business". They include processors, server power supplies, other server components, and storage and communication equipment. "Supply side on the other hand are systems that support the demand side. They include the UPS, power distribution, and cooling, lighting and building switchgear.

The breakdown of power drawn in this analysis shows that demand side accounts for about 52 percent of total consumption while Supply-side systems account for about 48 percent of consumption.

S/N	Category	Components	Percentage Energy Consumption
1	Demand Side (52%)	Processor	15
2		Server Power Supply	14
3		Other Server	15
4		Storage	4
5		Communicating Equipment	4
6	Supply Side (48%)	UPS	5
7		Power density Units PDU	1
8		Cooling Systems (CRAC)	38
9		Lighting	1
10		Building Switchgear/ MV Transformer	3

Table 1-2; Predicted US electricity use for data centers for 2006-2010 from EPA.

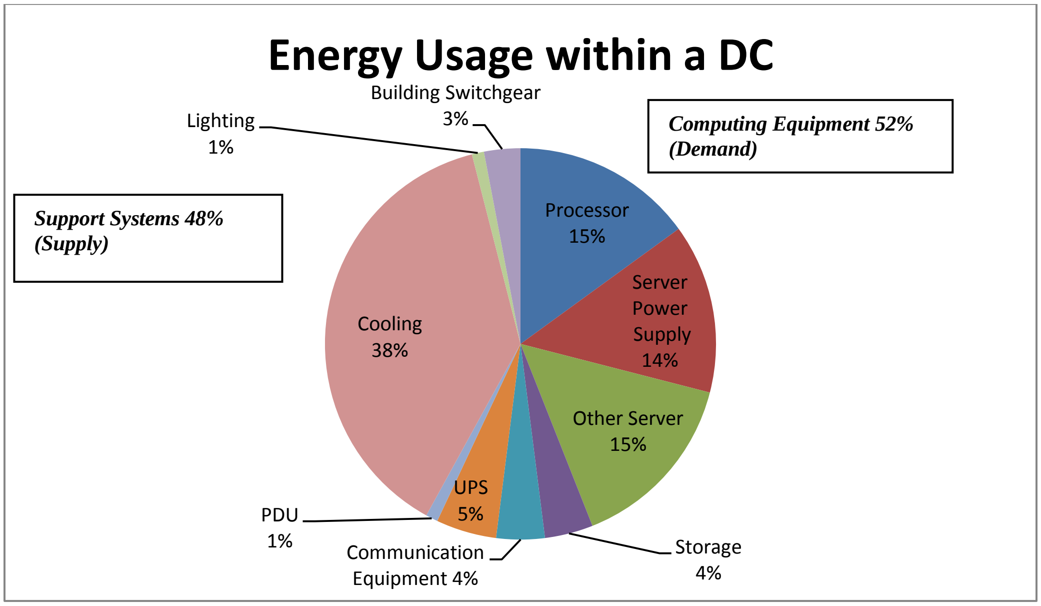


Figure 1-4: Analysis of a typical 5,000-square-foot data center showing percentage usage of computing side and supply side. (Emerson Network Power Model).

1.4. Data Center Power Management and Optimization

The enormous amount of incentives to reduce energy cost of DC lead to various approaches and methodologies; on the IT equipment side various methods of energy reduction has been adopted. This includes;

1. Power Management System
2. Server Optimization
3. Increased Processor Efficiency
4. Increased Power supplies efficiency

On the Supply side, cooling systems, which is the largest power usage in the support systems part of the DC, has received the highest level if attention. The cooling systems (Computer Room Air-Conditioning systems) are used for cooling electronic equipment. Various methods of reducing energy consumption by cooling systems have been adopted. They include;

1. Air-Side Economizer
2. Cooling Best Practices
3. Variable Capacity Cooling Systems
4. High-Density Supplemental Cooling
5. Monitoring and Optimization

1.5. Air - Side Economizer

Air – side economizer also known as free cooling is the introduction of outside into data centers during favorable weather conditions to cool electronic equipment. Silicon devices reach functional limits between 85 – 105^{0}C (185 – 221^{0}F) range [1]. Permanent damage is expected occurs at 15 - 25^{0}C higher. Outside air can be introduced into data centers in locations with favorable weather conditions. A typical Air-side economizer that delivers outside at specific temperature and humidity is shown in figure 1-5 below. Figure 1-6 shows the schematic of outside here introduction into a typical data center while figure 1-7 depicts the air – side cooling map over the United State.

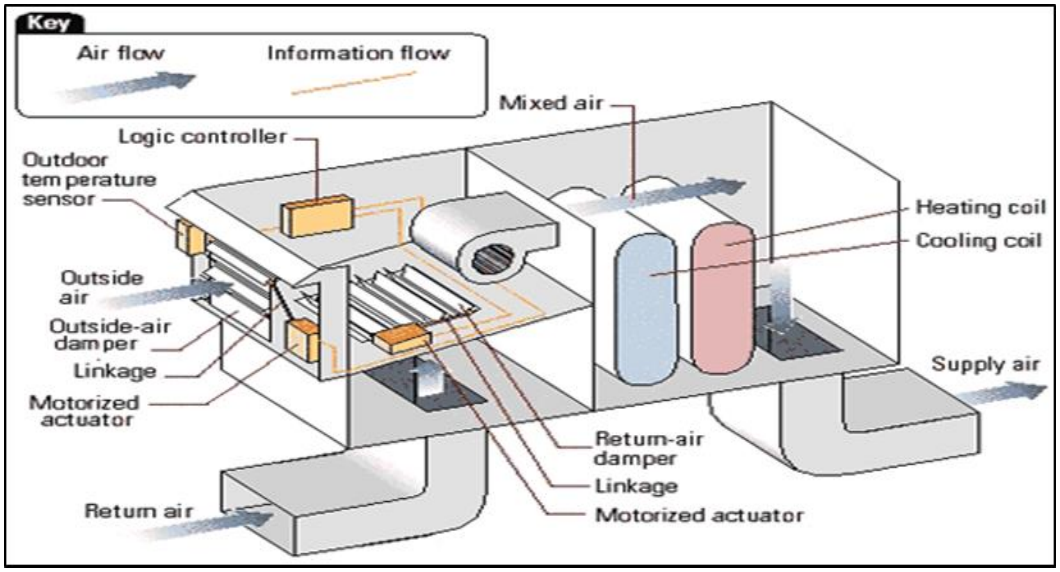


Figure 1-5; Air-side Economizer System

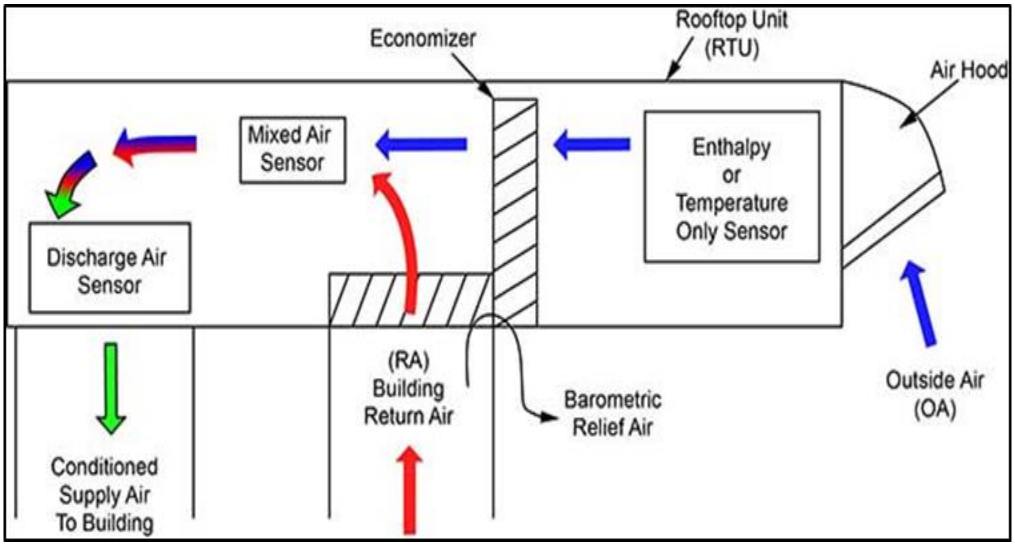


Figure 1-6; Schematic of outside air-flow into data center

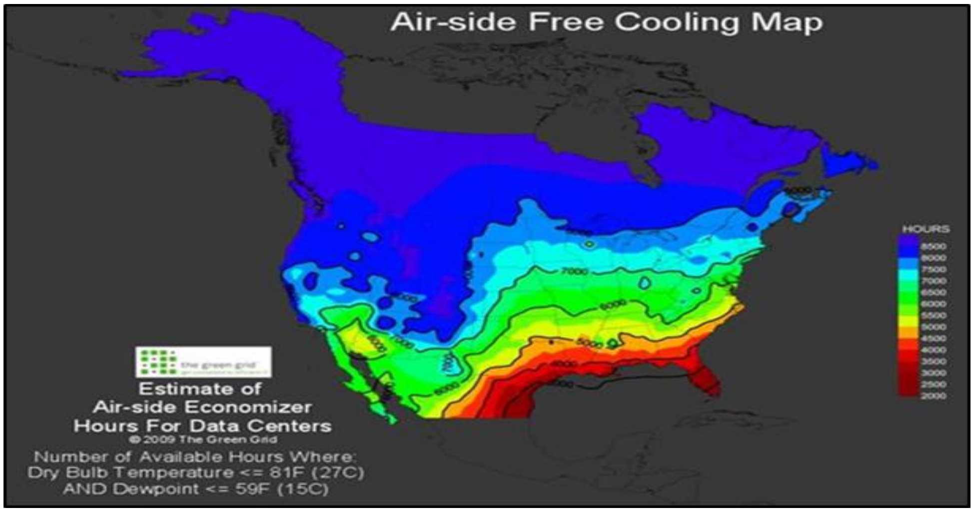


Figure 1-7; US Air-Side Cooling Map (Courtesy of DOE and the Green Grid)

1.6. Contamination

When outside air is introduced into the data center for cooling, it introduces potential contamination present in the atmosphere. The contaminants can be grouped into two separate categories.

a. Particulate Contaminants

b. Gaseous Contaminants

Particulate contaminants are airborne particles that are either coarse-mode or fine mode particles. Particles are generally dusts or ionic salts present in the atmosphere in a diameter range of approximately 2 µm to 20 µm. The coarse particle can generally be removed by using high efficiency filters. There are filters (MERV 11, 13 etc.) installed to remove mostly coarse particles from outside air before been introduced into data center. The fine modes are very difficult to remove with the filters and consequently have more negative impact on the electronic equipment than the coarse mode particles. Some of these particles are hygroscopic in nature and can therefore absorb moisture. Some of these particles particularly the salt contaminants absorb moisture, get wet and become electrically conductive. These wet salts can become reactive and corrode metals. They can also be a source of current leakage and electric short circuits in circuit boards.

Failures were reported on circuit boards in the telecommunication industry due to wetted deposited particles on circuits. [7,8]. The deliquescence relative humidity (DRH) of a contaminant is a term used to describe the %RH above which the contaminant (especially salt) will absorb moisture, get wet and become electrically conductive.

ASHRAE recommended that the data center particulate contamination levels be kept clean to ISO class 8 [9] with strictness to 95% upper confidence limit [10]. Filters MERV 8 can achieve this continuously [11]

Gaseous contaminants

Compliance with Restriction of Hazardous Substance (RoHS) that came into effect in July 2006, requiring the elimination of lead or lead free solders from electronic equipment, leaving manufacturers to seek alternatives. Some of the replacements element and processes of using those alternatives have been known to be susceptible to gaseous contamination. This is evident in creep corrosion in environments where lead has performed without these failures now reported. [12]

Gaseous contaminants can either be natural occurring air-borne gases or can be from human activities. The most common gases identified so far are Sulfur Dioxide (SO_2), Hydrogen Sulfide (H_2S), Nitrogen Dioxide (NO_2), Chlorine (Cl), Hydrogen Chloride (HCl) Ammonia (NH_3) etc. These gases either act together as mix flowing gases or alone on IT equipment to form undesirable compounds. For example Sulfur bearing gases can react with silver components to form Silver Sulfide (Ag_2S) causing the failure of the component. For locations with known gaseous contamination levels, gas filtration of the inlet air as well as air inside the data center is recommended [1].

1.7. Scope of this Work

1.7.1 Objectives

The objectives of this dissertation are;

- Determine the effect of temperature and relative humidity, under real data center conditions,
    - Corrosion rates of Copper coupons
    - Corrosion rate of Silver coupons
    - Exposing thin films and tracking real time changes
    - Qualitative evaluation of Corrosion reliability of IT Equipment of exposed IT components.

This work is focused on gathering real life data from an experimental data center jointly owned by University of Texas Arlington and Mestex Corporation located in a polluted industrial area in Dallas. The direct and indirect evaporative cooling cools the data center.

The location of the coupons and thin films inside the data center will as per ASHRAE requirements of ¼” and ¾” heights in front of the rack. This will be measured across different locations within the data center to assist in determining the distribution of the contaminants.

1.8. Contributions

This work provides basis to IT equipment manufacturers to provide warranty for their products in a G2 environment. IT equipment manufacturer can separately subject their equipment at the experimental data center in order to determine the duration that their equipment can reliably operate. As this is the first time IT equipment has been exposed to air quality classified as G2 while in operations and excursions in temperature and relative humidity outside the ASHRAE recommended environment. This provides basis for which ASHRAE can expand the operating envelop for the allowable and recommended operating envelope for temperature and relative humidity.

IT equipment manufacturers can use this data for other data centers in other geographies outside the United States.

Chapter 2

Literature Review

This section contains a review of gaseous and particulate contamination measuring techniques used in the characterization of any environment. The technique adopted by electronic manufacturing community to determine exposure levels of electronic equipment to the environment without risk of damage. A further review of copper and silver corrosion reported over the years and their effect on electronic equipment. Finally operating and allowable envelope recommended by ASHRAE are reviewed.

2.1. Direct Gas Concentration Measurement

This is the direct introduction of gases of known concentrations into environmentally controlled chambers having coupons. The gases can be introduced as a single gas or in combination with other gases.

According to ANSI/ISA – 71.04-2012 “The synergistic effects of various combinations of corrosive gases make the determination of severity levels of complex when only examining gas concentration data. In addition to the contaminant gases themselves, temperature and humidity also have a major impact on the corrosion rates”. Also “gaseous limits for the reliable operation of electronic equipment cannot be specified in terms of the concentrations of gaseous contaminants in the air, metal corrosion is too complex a process to allow its rate to be determined from gaseous chemical composition.

Table 2-1 below describes reactivity levels from gas concentrations levels in parts per billion (ppb)

Table 2-1; ISA – 71 .04-1985

Severity Level	Copper Reactivity Level	Gaseous Contaminants (in ppb)						
		Group A				Group B		
		H_2S	SO_2, SO_3	Cl_2	NO_x	HF	NH_3	O_3
G1 – Mild	<300Å	<3	<10	<1	<50	<1	<500	<2
G2 – Moderate	<1000 Å	<10	<100	<2	<125	<2	<10,000	<25
G3 – Harsh	<2000 Å	<50	<300	<10	<1250	<10	<25,000	<100
GX – Severe	≥2000 Å	≥50	≥300	≥10	≥1250	≥10	≥25,000	≥100

This technique provides approximate reactive levels as described in Table 2-2 above and can be used for prediction at relative humidity less than 50%. Direct gas monitoring technique are still used to form different contaminants in the laboratory and estimate severity levels [16]

2.2 Reactivity Monitoring

Another method is the “reactivity monitoring” which is more convenient and is a quantitative method. This method can be used to determine the corrosive potential of an environment by measuring the total corrosion film thickness on specially prepared copper coupons. Further studies [14, 15] by others using “laboratory and field–exposed coupons have shown that using copper coupons alone can significantly under or overstate this corrosive potential”.

This method exposes coupons to the environment for 30days and the resulting corrosion product thickness is evaluated by using coulometric reduction and chemistry.

Table 2-2; Description of Severity level of an environment based on “reactive monitoring” with copper

Severity Level	Copper reactivity level	Description
G1 Mild	300Å/month	An environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability
G2 Moderate	300 - 1000Å/month	An environment in which the effects of corrosion are measurable and may be a factor in determining equipment reliability
G3 Harsh	1000 - 2000Å/month	An environment in which there is high probability that corrosive attack will occur.
GX Severe	>2000Å/month	An environment in which only specially designed and packaged equipment would be expected to survive

Using copper coupons alone has its own limitation because of its inability to determine accurately the presence or absence of Chlorine. On the other hand using Silver alone also has its own limitation when used alone because it more sensitive to Chlorine.

Therefore it is important to use combination classification coupons (CCC’s) using both copper and silver for accurate results for environmental classifications [14].

The use of Combination Corrosion Classification coupons as adopted in these experiments (CCC’s) using both Copper and Silver was then proposed as the most accurate classification of an environment.

2.3 Copper and Silver in Electronic Equipment

Since the directive from European Union [17] where use of certain hazardous substances were prohibited in electrical and electronic industries. The restriction were on the use of six substances in electrical and electronic equipment:

1. Mercury (Hg)
2. Lead (Pb)
3. Hexavalent chromium (Cr(VI))
4. Cadmium (Cd)
5. Polybrominated biphenyls (PBB)
6. Diphenyl Ethers (PBDE).

The consequences of these restrictions led to the elimination of lead in electronic products. This led to a challenge in the electronic industry, as lead is a common component in the manufacture and assembly of components on circuit boards. PCB has been one of the most common mechanical support and electrical connections between electronic components with conducting layers. The conducting layer surfaces are typically made of thin copper foil plated with lead based solder to protect it from oxidation and potential damage. This plating is deposited via a process called the hot air solder leveling (HASL). This process has been in use for many years but now made obsolete by the restrictions. Other alternatives were then introduced, amongst which we have immersion silver (ImmAg) and organically coated copper (OCC) for board finishes that became a standard surface finishes [18]. However this new surface finishes led to certain corrosion issues that were originally not experienced with the HASL process.

“In a study by Rockwell Automation [19] looking at lead-free finishes, four alternate finishes were subjected to an accelerated mixed flowing gas corrosion test, [20] Important findings are summarized below;

1. The immersion gold (ENIG) and immersion silver (ImmAg) surface finishes failed early in the testing. These coatings are the most susceptible to corrosion failures and are expected to be much more susceptible than traditional HASL coatings. The use of these two coatings may make the PCB the weak link with regard to the sensitivities of the electronic devices to corrosion.

2. None of the coatings can be considered immune from failure in an ISA Class G3 environment.

3. The gold and silver coatings could not be expected to survive a mid to high Class G2 environment based on these test results.

2.4 Copper and Silver Corrosion on Electronic Equipment

When electronic components (usually metals) deteriorate because of reaction between the metal and the environment forming a different substance we say corrosion has taken place. And the metallic component can no longer function as designed. This is usually by chemical reaction between the metal and airborne contaminants and further aggravated by the temperature and or humidity. This can occur at relative humidity (RH) above 50% it can also occur at low relative (RH) in combination with temperature and type of contaminants present [21].

Corrosion product generally forms when you have a corrosive gas and some amount of water vapor in contact with a metal like Copper of Silver chemically reacting together. The product of the reaction forms layers on circuits and potentially leads to electrically shorting of closely spaced features on PCBs and silver termination metallization in surface-mount resistors.

Copper and Silver coupons has been regarded in the industry as the best way [35] to carry out corrosion monitoring in a real world data centers particularly in polluted regions of the world.

2.5 Corrosion types on Electronic Equipment

The two most common reported types of corrosion in electronic equipment according to [20] are Conventional corrosion and whisker growth.

"Conventional Corrosion is the generally occurring direct attack from by corrosive gases for form conductive salts. They include;

2.5.1 Creep Corrosion

This is a type of corrosion where corrosion propagates from its starting point. [19] When edges are of a certain electronic metals corrode, and the corrosion product grow from the edges and slowly spread across the surface as shown below it is known as creep corrosion. "*This is a mass-transport type of migration where the corrosion products moves across the surface eventually coming in contact with electrical connections".*

This corrosion type has been documented as long-term reliability risks [22]

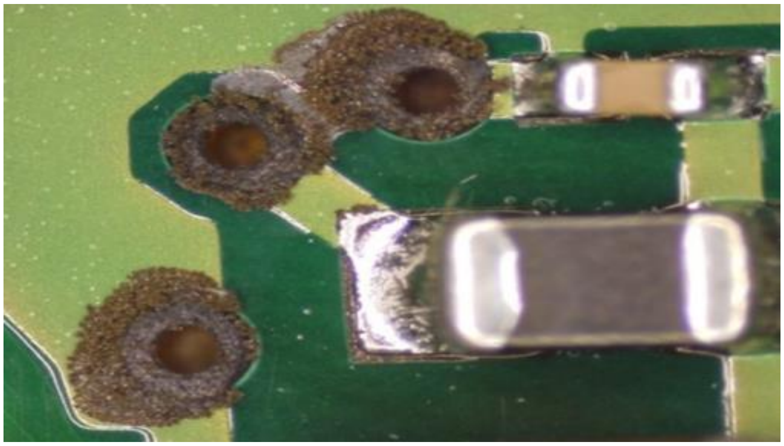


Figure 2-1; Creep Corrosion

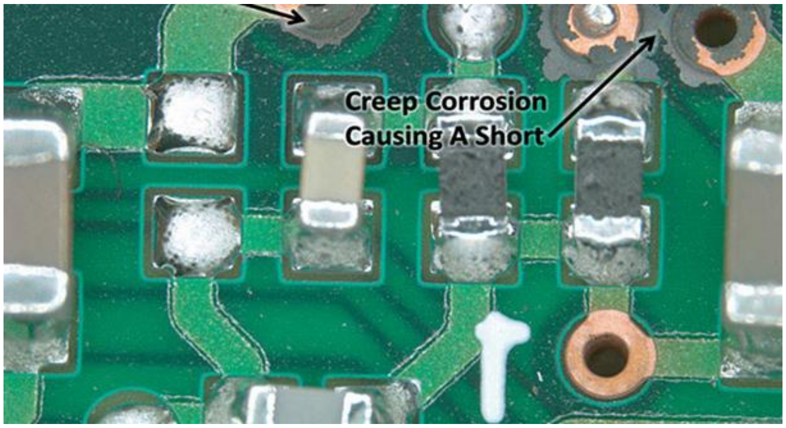


Figure 2-2; Creep Corrosion Causing short Circuit

2.5.2 Whisker Growth

This is a type of corrosion that typically occurs with the process of electroplating tin as surface finishes. Tin whiskers have been reported [19] to grow between connectors causing short circuits between closely-spaced circuit components. “*This is a type of corrosion where microscopic crystals grow from the surface of a conductive metal. This is caused by the presence of sulfide molecules e.g. Silver Sulfides on silver surface.*

The associated effects of whisker growths are found at edge connectors, pin Connectors, wire-wrap connections and Electrical systems.

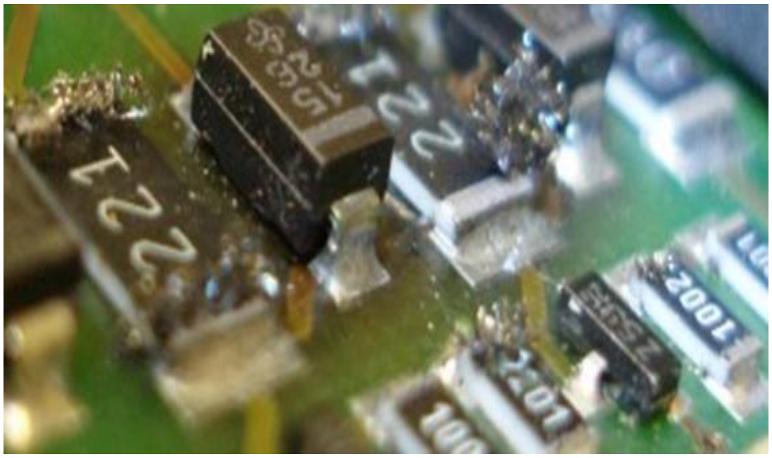


Figure 2-3; Creep Corrosion on PCB board

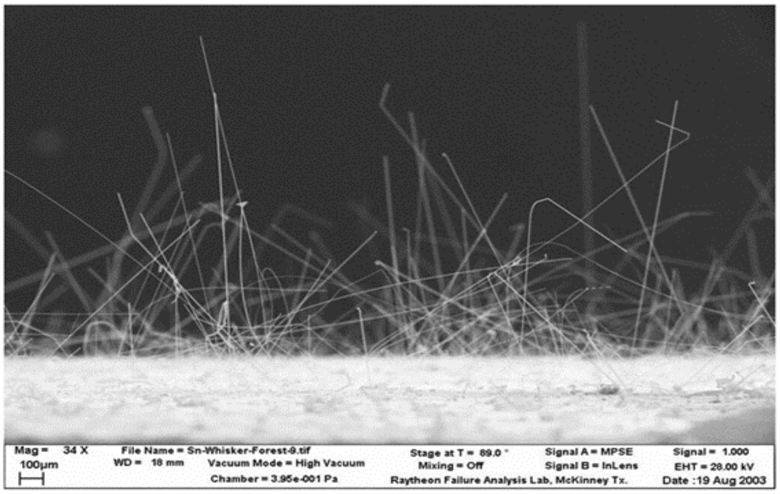


Figure 2-4; Whiskers

2.6 Gaseous Contaminants

The following gases were considered by ISA 1985 as main gaseous contaminants responsible for corrosion in data center.

1. Acidic gases (e.g. H_2S, SO_2, N_xO, Cl, HF)
2. Caustic gases, (e.g. NH_3,)

3. Oxidizing gases (e.g. O_3)

An environment can have predominant type of gases or a combination of the gases at different levels of concentrations. The various types of gases are described in table 2-3 below

Table 2-3: Common pollutants and sources (ISA 1985)

Sources of Reactive Environmental Contaminants (ISA 1985)			
Constituent	Symbol	Category	Common Sources
Acetic acid	CH_3COOH	Gas	Semiconductor manufacturing, wood and wood products, photo developing
Active organic nitrogen	N_2	Gas	Automobile emissions, animal waste, vegetable combustion, sewage, wood pulping
Ammonia	NH_3	Gas	Microbes, sewage, fertilizer manufacture, geothermal, steam, refrigeration equipment, cleaning products, reproduction 9blueprint) machines
Arsine	AsH_3	Gas	Semiconductor manufacturing
Carbon	C	Solid	Incomplete combustion (aerosol constituent), foundry
Carbon monoxide	CO	Gas	Combustion, automobile emissions, microbes, trees, wood pulping
Chloride ions	CO	Gas	Aerosol content, oceanic processes, ore processing

Chlorine, Chlorine dioxide	Cl_2, ClO_2	Gas	Chlorine manufacture, aluminum manufacture, paper mills, refuse decomposition cleaning products
Ethylene	C_2H_4	Gas	Fruit, vegetable, cut flower storage & transportation
Formaldehyde	HCHO	Gas	Wood products, floor & wall coverings adhesives, sealants, photo developing, tobacco smoke
Halogen compounds	HBr, HI	Gas	Automobile emissions
Hydrocarbons (alcohols, aldehydes, ketones, organic acids)	HC, THC	Gas	Automotive emissions, fossil fuel processing, tobacco smoke, water treatment, microbes. Many other sources, both natural and industrial, paper mills
Hydrogen Chloride	HCl	Gas	Automobile emissions, combustions, oceanic processes, polymer combustion
Hydrogen fluoride	HF	Gas	Fertilizer manufacture, aluminum manufacture, ceramics manufacture, steel manufacture, electronic device manufacture, fossil fuel
Hydrogen sulfide	H_2S	Gas	Geothermal emissions, microbiological activities, fossil fuel processing, wood pulping, sewage treatment, combustion

			of fossil fuel, auto emissions, ore smelting, sulfuric acid manufacture
Inorganic dust		Solid	Crystal rock, rock and ore processing, combustion, blowing sand and many industrial sources
Mercaptans	S_8, R-SH	Gas	Foundries, sulfur manufacture
Oxides of nitrogen	N_xO	Gas	Automobile emissions, fossil fuel combustion, blowing sand many industrial sources
Ozone	O_3	Gas	Atmospheric photochemical processes mainly involving nitrogen oxides and oxygenated hydrocarbons, automotive emissions, electrostatic filters
Sulfur dioxide	SO_2, SO_3	Gas	Combustion of fossil fuel, auto emissions, ore smelting, sulfuric acid manufacture, tobacco smoke

2.7 Particulate Contaminants

Particulate contaminants also known as particulate matter can be either in solid of liquid phase. The source of these contaminants can be from air or within as a result of activities within the data center. When they are from outside air they can come into the data center through the cooling facilities. The geographical location of a data center determines the type of particulate that can infiltrate through the cooling systems into the building. If a data center is located near the ocean it is expected that salt particulates can infiltrate the facility. Similarly if the location has a high level of industrial activities, it is expected that soot or ashes from exhaust of machinery can be transported via wind through the air-handling unit to the data center. In locations with high level of dust activities it is also likely that wind can transport the dust into the data center.

There have been several particulate induced failures that has been reported over the years. The mode of failure also well documented in ASHRAE 2009a includes

- *Mechanical effects*
- *Chemical effects*
- *Electrical effects.*

Particulate matter are found in various sizes from 2.5 – 15 µm. These particles settle on electronic equipment like printed circuit board and absorb moisture from the environment. When enough moisture has been gathered it impacts the insulation on the circuit board leading to short circuit of the component. A term called deliquescent relative humidity of the particulate is the humidity at which the particulates absorbs an amount of moisture enough to be wet and potentially cause degradation of the circuit or electronic component. Studies by [37] showed a leakage current traced to accumulation of dust and consequently moisture absorption leading to current leakage.

ISO 14644-1 shown in table 2-4 below describes the air cleanliness classification with reference to maximum permissible concentration with reference to the particle sizes.

Table 2-4: ISO Air Cleanliness

ISO Class	Max. no. of particles in each m^3 of air equal to or greater than the specified size					
	Particle Size					
	>0.1 µm	>0.2 µm	>0.3 µm	>0.5 µm	>1 µm	>5 µm
Class 1	10	2				
Class 2	100	24	10	4		
Class 3	1000	237	102	35	8	
Class 4	10,000	2370	1020	352	83	
Class 5	100,000	23,700	10,200	3520	832	29
Class 6	1,000,000	237,000	102,000	35,200	8320	293
Class 7				352,200	83,200	2930
Class 8				3,520,000	832,000	29,300
Class 9					8,320,000	293,000

For particulates matter filtration is a highly popular method of elimination or reducing its effect. If particulates can be prevented from getting into the data center then through openings, ducts then failures from PM will be eliminated.

There are various filters for different PM sizes. Filters are also classified by their Minimum Efficiency Reporting value MERV. A term commonly used in the industry to categorize filters.

There is an ASHRAE 52.2-2007 filter standard used in classifying and specifying appropriate filters for different particle sizes. Table 2-5 below extracted from ASHRAE 52.2 describes different categories of filters and classified numbers and their suitable particle size. MERV size 8 are generally recommended for standard data center using CRAC units while MERV 11 and above are recommended for data centers deploying air-side economizer technology.

Table 2-5: MER values from ASHRAE Standard 52.2

ASHRAE 52.2						
MERV	3-10 µm	1-3 µm	0.3-1 µm	Arrestance	Dust Spot	Dust Spot
1	<20%	-	-	<65%	<20%	
2	<20%	-	-	65% - 70%	<20%	>10 µm
3	<20%	-	-	70% - 75%	<20%	
4	<20%	-	-	>75%	<20%	
5	20%-35%	-	-	80% - 85%	<20%	
6	20% - 50%	-	-	>90%	<20%	3-10 µm
7	20% - 70%	-	-	>90%	20% - 25%	

8	<70%	-	-	>95%	25% - 30%	
9	<85%	<50%	-	>95%	40% – 45%	
10	<85%	50% - 65%		>95%	50% - 55%	1-3 µm
11	<85%	65% - 80%		>98%	60% - 65%	
12	>90%	>80%		>98%	70% - 75%	
13	>90%	>90%	<75%	>98%	80% - 90%	
14	>90%	>90%	75% - 85%	>98%	90% - 95%	0.3-1 µm
15	>90%	>90%	85% - 95%	>98%	>95%	
16	>95%	>95%	>95%	>98%	>95%	
17	>99%	>99%	>99%		99%	
18	>99%	>99%	>99%		99%	0.3-1 µm
19	>99%	>99%	>99%		99%	
20	>99%	>99%	>99%		99%	

2.8 ASHRAE Recommended and Allowable Classes

IT equipment manufacturers provides warranty for their equipment as long as they are operated with the recommended region by ASHRAE shown in figure 2-5 below

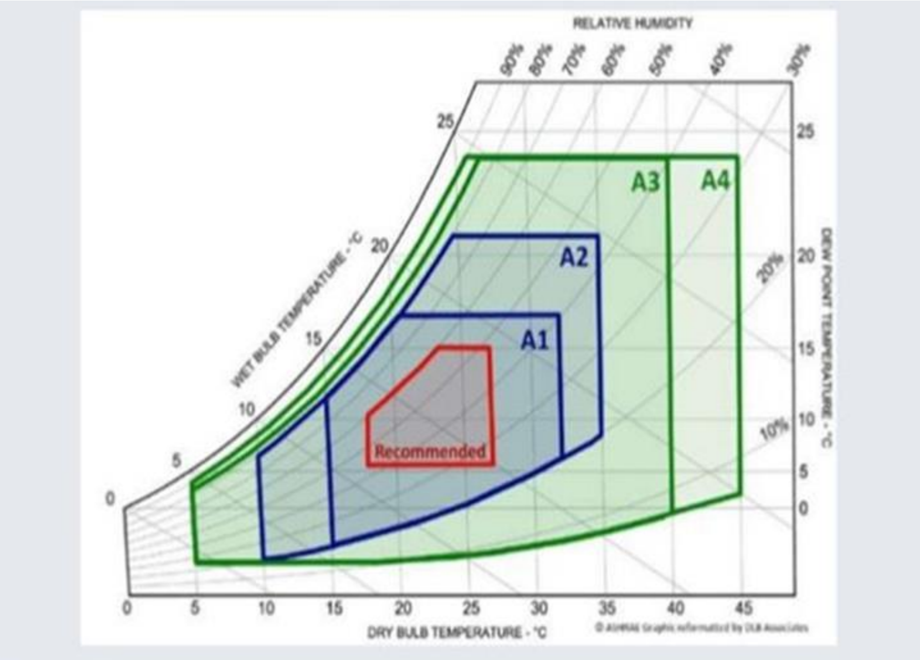


Figure 2-5; ASHRAE recommended and allowable ranges.

Furthermore the manufacturers have also tested their equipment to certain allowable classes also shown above. Contaminants limit the temperature-humidity envelope equipment can reliably operate.

Region A1 – A4 also has associated problems. At 80-85% relative humidity, most dust will get wet and support high levels of leakage currents between closely spaced features on PCBs. The failures will probably be intermittent and therefore difficult to diagnose.

In addition, high relative humidity will aggravate

- Creep Corrosion
- Ion migration in/on PCBs
- Component corrosion

- Connector corrosion

Moisture absorption by PCB laminates may degrade machine performance and reliability.

Table 2-6; ASHRAE “Environmental Guidelines for Datacom Equipment-Expanding the Recommended Environmental Envelope” 2008

ASHRAE Recommendations	IT equipment environment
Low end temperature	18^0C
High end temperature	27^0C
Low end moisture	5.5^0C dew point
High end moisture	60% RH and 15^0C dew point

Chapter 3
Coulometric Reduction Technique for Corrosion Coupons and Self- Heating Effect of Thin Films

3.1 Coulometric Reduction Technique for Corrosion Coupons

Coulometric reduction technique is a standard test method for the evaluation of surface films described in ASTM B825 and summarized below.

Exposed coupons after exposure over a period of time are analyzed for products formed on the film surfaces. A constant current density applied in an *electrolytically conductive solution,* [29] *and resulting variations in potential measured against a standard reference electrode in the same solution are followed as a function of time.*

In this work the corrosion product formed on the surface of the films are analyzed by Coulometric method. They provide information on the corrosion products and accumulated thickness that is required in the determination of the monthly rate. The surfaces are first evaluated using scanning X-ray photoelectron spectroscopy on the exposed coupons. This helps to determine the compositions of compounds or products on the surface of the coupons. The depths, thickness, peak positions of the products are also determined. The Coulometric plots of potential-time curves are then recorded with the application of a constant current density using a Potentiostat.

Different corrosion products will be reduced at different potentials corresponding to their respective potentials. For instance the following has been reported [29] to have been reduced at for CuO were between minus 0 - 600mV, for Cu_2O between minus 600 - 900mV for Cu_2S and AgCl was between minus 900 – 1200mV. Ag_2S was between minus 0 – 700mV.

Figure 3-1 below illustrates a typical schematic of a Coulometric set-up with Ag electrodes, current source and timer. Also shown is an argon gas source, indication unit and the reduction chamber.

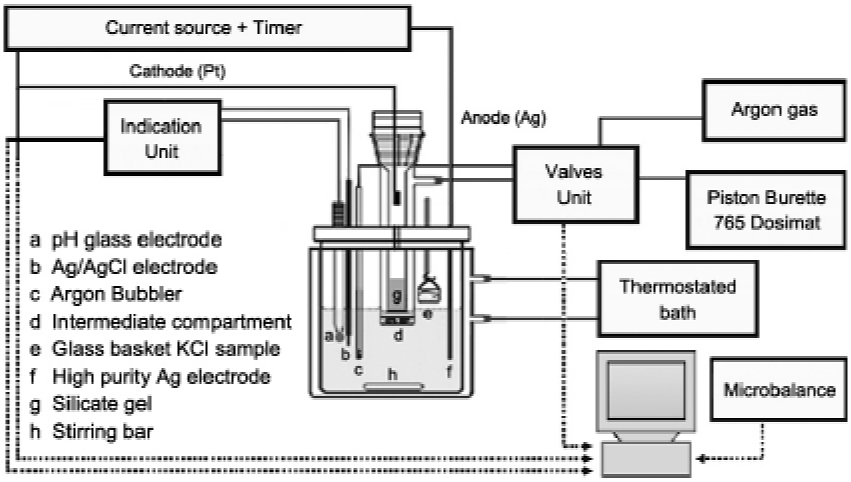


Figure 3-1: Schematic diagram of a Coulometric Cell (Courtesy of Researchgate.net).

Typical electrode potentials to determine potential requirement for the scanned products is shown in figure 3-2 below. After each reduction of the corrosion product and the time to reduce to respective elements and or compounds. A plot similar to figure 3-3 is then plotted as a profile to describe the corrosion products. Based on the formulae provided in ASTM B825 the total mass of known substance was calculated as follows,

$$M_T = \frac{IT \times 10^3\, M}{NF} \qquad (3\text{-}1)$$

Where

M_T = mass, µg

I = Current, mA

T = time, s, to reduce known substance

M = gram – molecular weight of that substance, g

F = Faraday's constant (9.65×10^4 C)

N = Number of faradays required to reduce a gram molecular weight of substance.

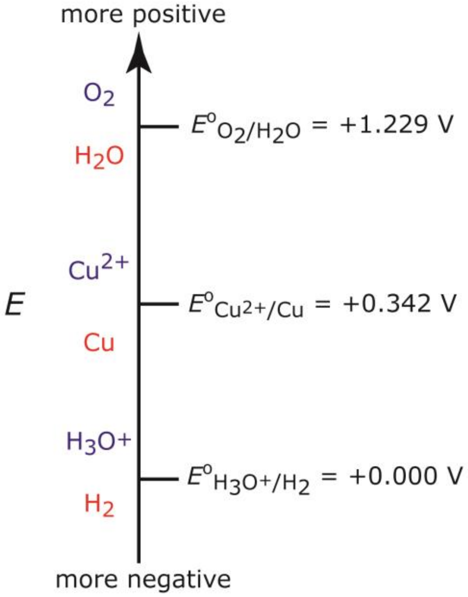


Figure 3-2: Schematic diagram of Electrode Potentials (Courtesy of chemwiki).

The equivalent film thickness of the substance T was calculated by the formulae

$$T = \frac{ITK}{a} \tag{3-2}$$

And K is

$$K = \frac{10^5\,M}{NFd} \tag{3-3}$$

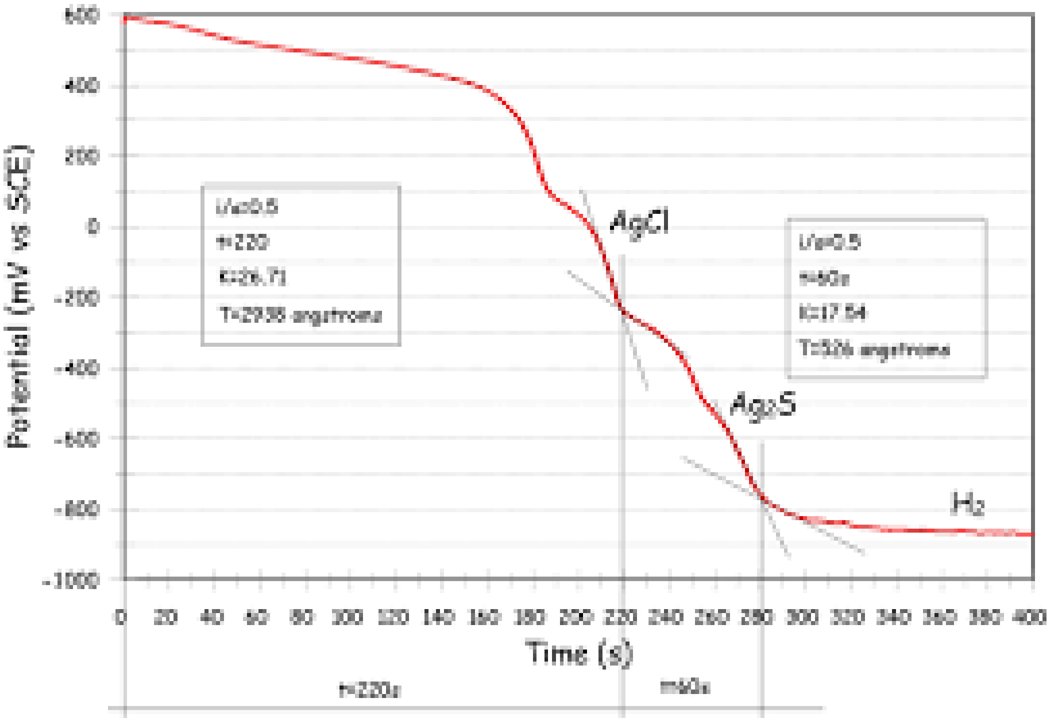


Figure 3-3: Diagram of Reduction Potential versus Time (Courtesy of Researchspace).

T = Thickness, Å (10^{-8} cm);

I = Current, mA;

T = time, s, to reduce a known substance;

A = Area of tested specimen, cm^2;

F = Faraday's constant (9.65×10^4 C)

D = Density of substance being reduced, g/cm^3, and

K = Conversion factor

3.2. Self Heating Effect of Thin films

Amongst several method of monitoring corrosion is the use of metal wire directly related to its electrical resistance. When the metal corrodes, its electrical resistance increases. This can be measured and related to the amount of metal loss to corrosion with time. This method of measurement has its demerits as well as some challenges when used as a monitoring technique in electronic equipment. One of the challenges is the fact that the level of measurement requires very small diameter wire. Another is to have the wires in a clean and reproducible manner. To address this issue thin films have been develop and used as a reactivity monitoring in electronic industries. They also provide real time measuring capability as an advantage over the conventional coupons.

When in use a constant current is supplied through the film and generate heating known as Joules heating or self-heating. These Joules heating is the heat energy produced from the supplied current and the resistance of the thin films. Figure 3-4 below shows a silver thin film used for corrosion monitoring.

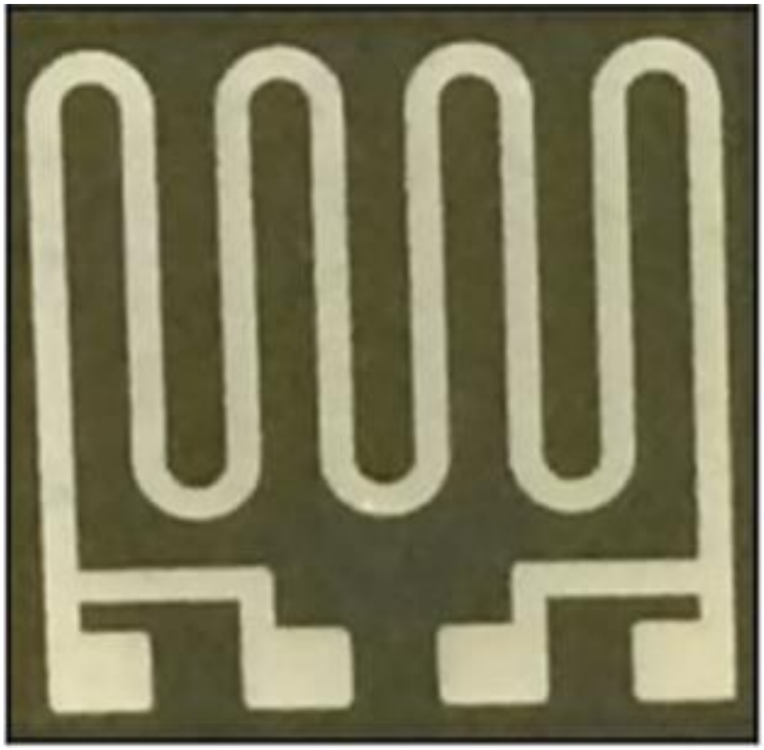


Figure 3-4: Silver Thin Film

Thin films are of the order of magnitude of nanometers in thickness. The thickness of the film in this evaluation is 1004nm and 772.3nm measured with a KLA Tencor’s profile at IBM York Town facility. This thin film is compressed on a silicon base of 0.5mm thick and a surface dimension of 15mm by 15mm. A typical set-up for laboratory measurement of corrosion rate is shown in figure 3-5 below:

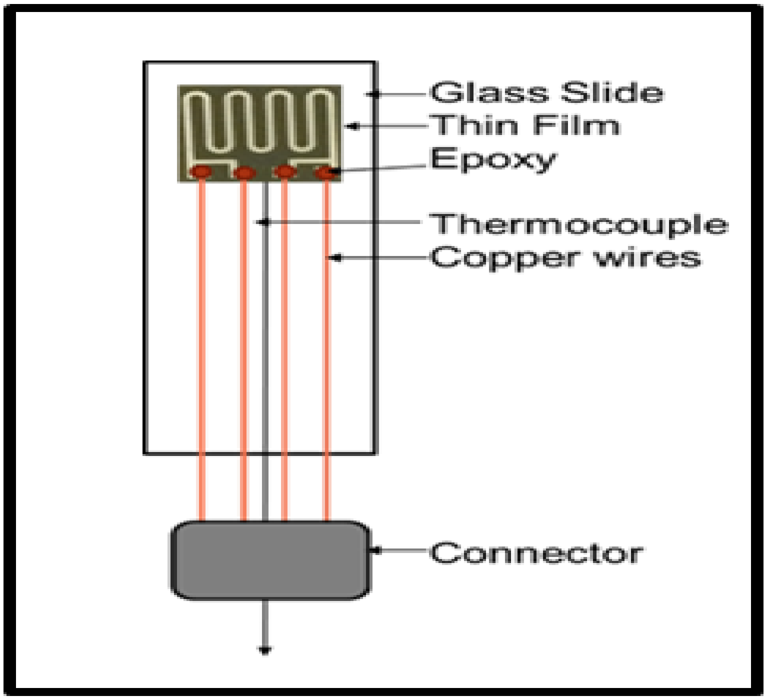


Figure 3-5: Thin Film Specimen (a) Cu & Ag [31]

This arrangement is then placed inside the oven maintained at a pre-determined temperature. The schematic is shown in figure 3-6 below.

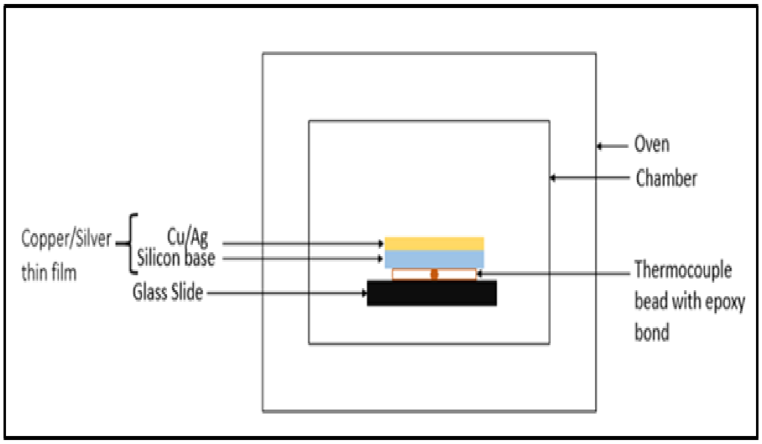


Figure 3-6: Schematics of thin film in the oven [31]

Details of the experiment are described in [31] where the oven is maintained at a given temperature and the thin films are supplied with a constant current. The question what would then be the effect of self-heating on the measured temperature at the thermocouple connected to the thin film or the surrounding air around the thin film.

3.3 Study Approach

To study this effect a model was created in ANSYS FLUENT [32] version 14.5

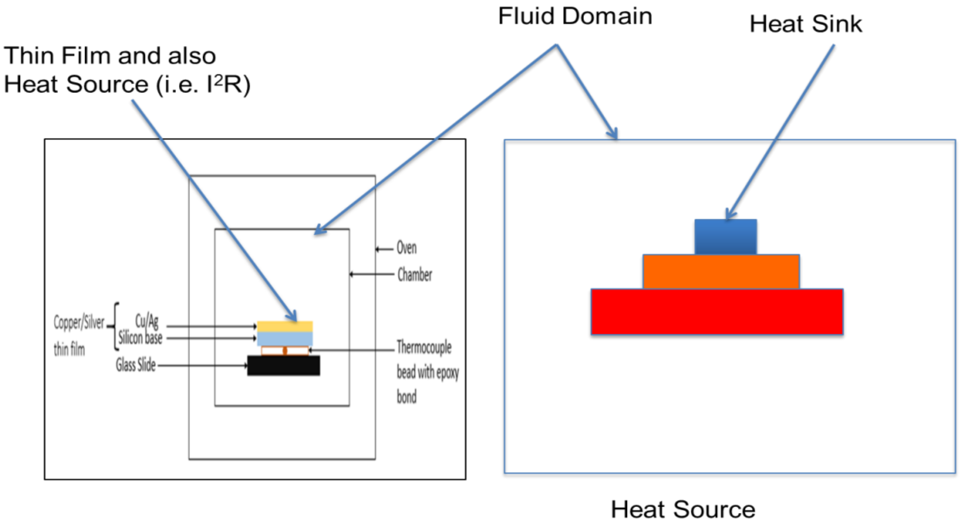


Figure 3-7: Thin Film and the Fluid Domain

The arrangement in figure 3-7 above is the experimental set-up for the exposure of thin films in an oven. The thin film at the top through which current is supplied is at the top. Under it is the silicon base to attach the thermocouple for measurement. The thermocouple is bonded to the glass base as well as the silicon base. This arrangement is placed in a chamber, which then in turn is placed in an oven for continuous supply of heat to maintain a specific temperature within the chamber. In this approach the surrounding air is the fluid domain around the thin film set-up.

The geometry with the dimensions below where then created in Ansys as shown in figure 20 below.

Length = 304.8mm

Width = 127mm

Height = 279.4mm

Silver/Copper Thin film = 25.4mm X 50.8mm

The model is then discretized with a mesh good mesh quality as shown in figure 3-8 below.

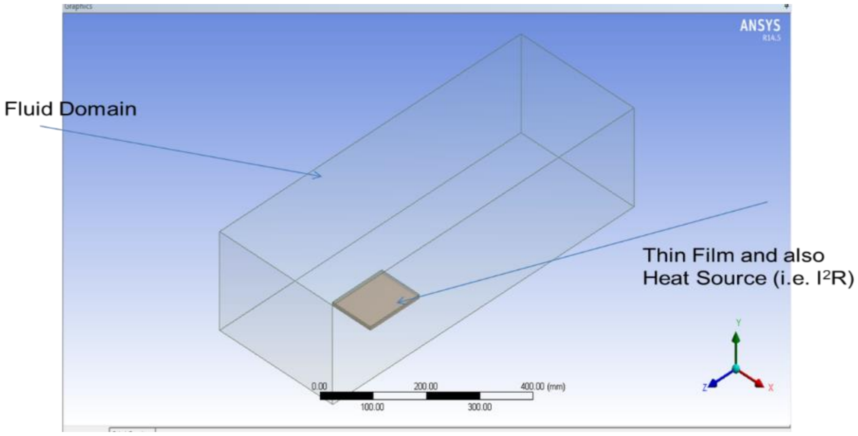


Figure 3-8: ANSYS Model of Thin film and the Fluid domain

After the discretization of the volume into appropriate mesh, the numerical solution considering velocity, pressure and temperature were calculated for each volume and computed for the entire domain. The Navier-Stokes equation for the above fluid/thermal flow problem is:

Conservation of mass

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (3\text{-}4)$$

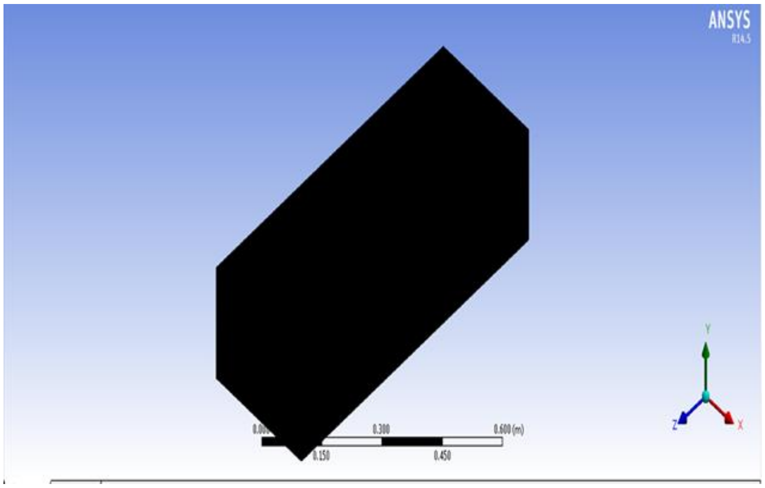


Figure 3-9: Mesh

Conservation of Momentum

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \beta g_i \theta \qquad (3\text{-}5)$$

Conservation of energy

$$\frac{\partial \theta}{\partial t} + \frac{\partial \theta\, u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\kappa\, \frac{\partial \theta}{\partial x_j}\right) + H \qquad (3\text{-}6)$$

Where i, j = summation indices

g_i = acceleration due to gravity in the y direction

H = Volumetric heat source

P = Instantaneous static pressure difference

t = time

u_i = instantaneous velocity component in y direction

x_i = Cartesian coordinates

β = Volumetric coefficient of expansion

κ = thermal diffusivity

θ = instantaneous temperature difference

ρ = density

ν = kinematic viscosity

The onset of turbulence specified by Reynolds number (Pipe flow) or Rayleigh number (Natural convention) for this geometry and for the conditions of flow indicates that it is a laminar. Therefore no requirement for viscous flow model is needed. The air changes with temperature and not pressure so an incompressible – ideal gas model was selected in the solver. Also since this is a natural convection problem the change in density with temperature is responsible for the flow. The contributions from pressure are very small and its effect on density is negligible. Therefore the incompressible idea gas density model is used.

Gravity was enabled in the solver, as it is very important in natural convention problems. Similarly the operating density selected as the far field temperature, which in this case is the inlet temperature from the oven. The pressures were for the inlet and outlet are zero.

The generated heat by the passage of current I was computed from

$$\mathrm{E}_g = \mathrm{I}^2 R \tag{3-7}$$

$$H = \frac{\mathrm{E}_g}{V} \tag{3-8}$$

From the supplied current and the resistance of the thin film the generated heat source is computed. Then divided by the volume of the thin film to obtain the volumetric heat source. Two separate computations were then made for to see the effect of the location of the thin film with respect to the both inlet and outlet.

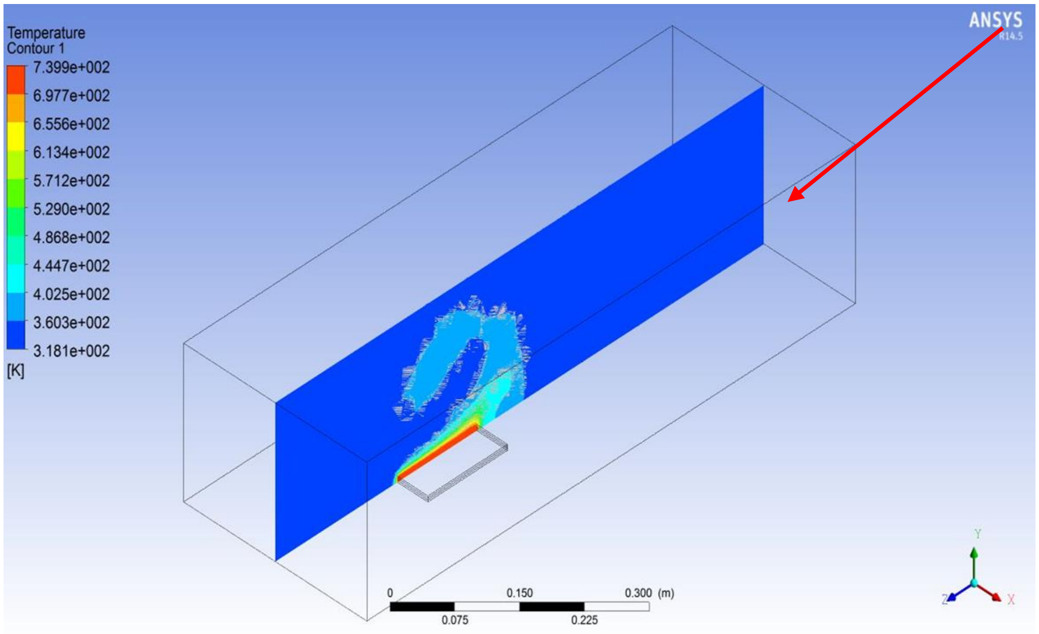


Figure 3-10: Temperature profile along the ZY axis (T1)

Figures 3-11 and 3-12 are the temperature plots of the thin film and the surrounding fluid domain around the thin film when the inlet conditions is on the right while the outlet is on the left. The inlet condition was set at 40^0C and at the outlet the total backflow temperature was set to 40^0C.

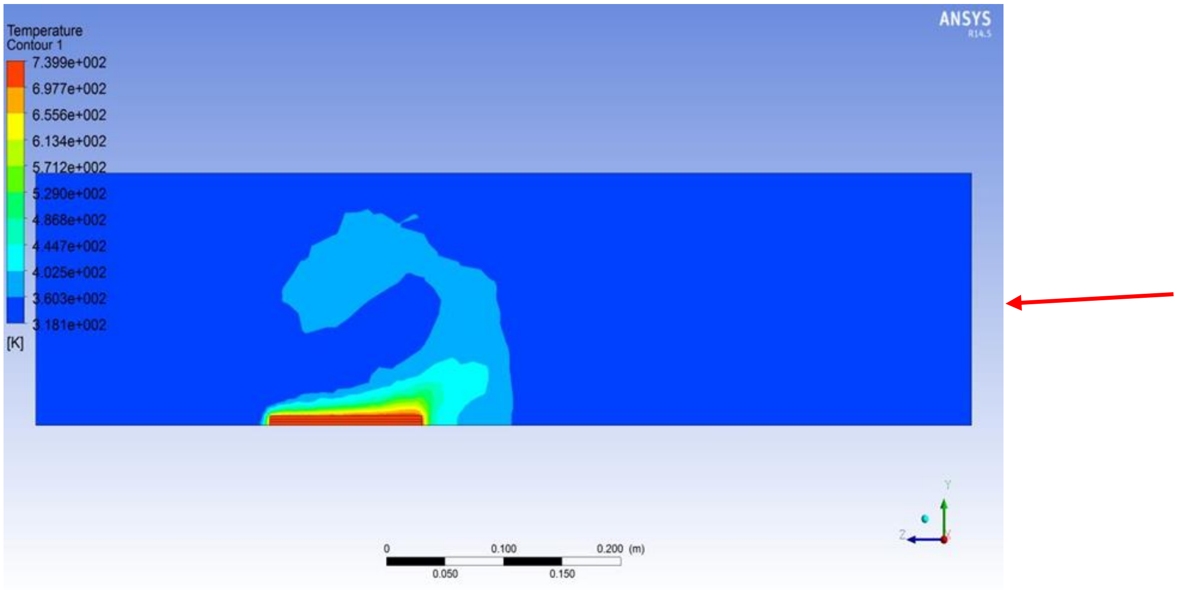


Figure 3-11: 2D Temperature profile along the ZY axis (T1)

3.4 Discussions

For the two simulations as expected there is uniform temperature distribution across the thin film in respective of the location of the film within the chamber and consequently the oven.

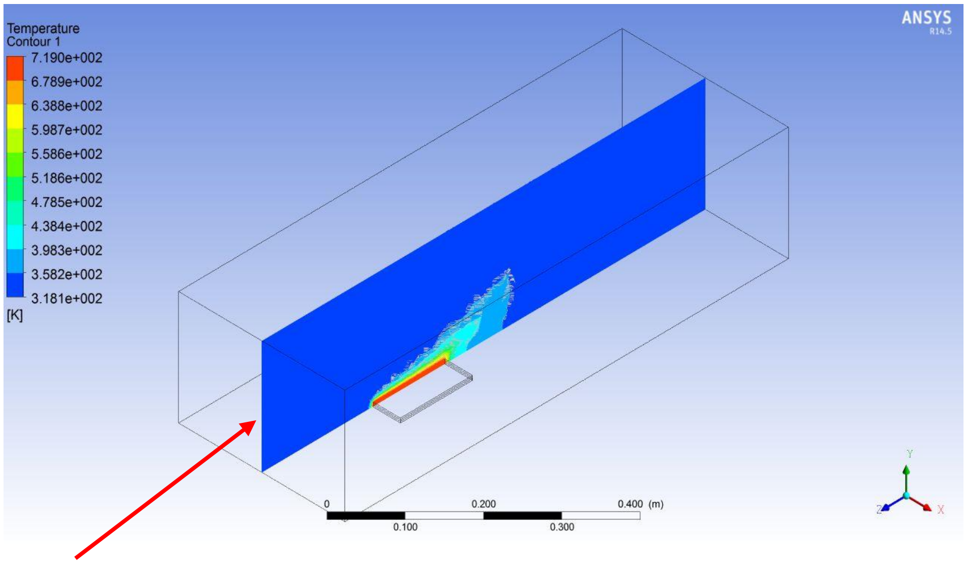


Figure 3-12: Temperature profile along the ZY axis (T2)

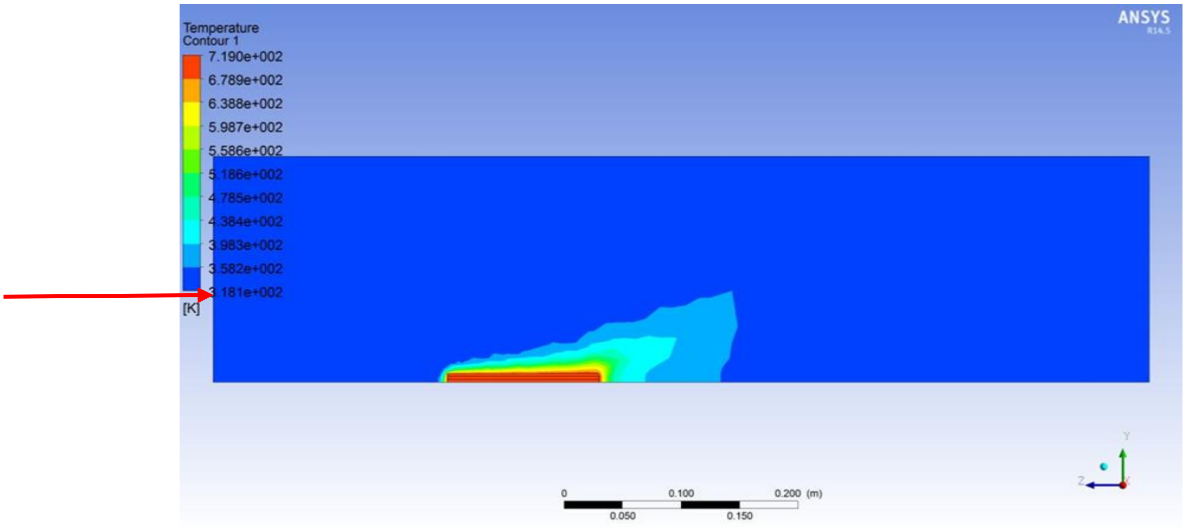


Figure 3-13: Temperature profile along the ZY axis (T2)

Chapter 4
Hardware Exposure to Temperature, Relative Humidity and Environmental Conditions

Gaseous contamination experiments have been undertaken in the past to provide justification for the use of corrosion classification coupons as a reactive monitoring and to evaluate environmental corrosion classification [26]. In this study corrosion classification coupon and corrosion sensors are both exposed to the same environment in order to compare both results under the same conditions.

4.1 Experimental Set up and Procedures

4.1.1 Laboratory testing of concentration effects on Coupons and MMT Sensors

To create a scaled model for CFD analysis in the evaluation of predictive corrosion rate an experimental set-up was developed. With a corrosion classification coupon CCC and sets of MMT corrosion sensors (Figure 26). Measurement and Management Technologies (MMT) [28] is an integrated sensor for monitoring and capturing environmental data in data centers. The two were deployed inside the corrosion chamber with the intent to compare the results.

Initial bench testing of the testing was performed with sensors to create a baseline before the introduction of contaminant source as shown in (Figure 4-1) below. This was done to test the connections of the sensors with the Lantronix software installed on the laptop. Temperature and RH values were then obtained and stored.

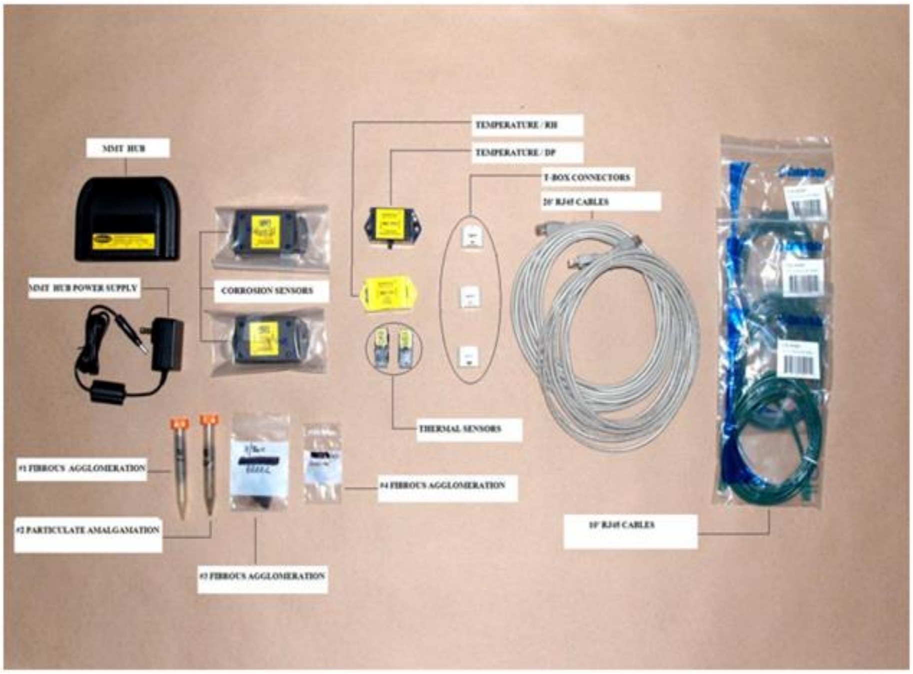


Figure 4-1: Temperature, Corrosion, Humidity & MMT Sensors

The set-up consisting of the following under listed components.

1. Test Chamber (Physical dimensions are L=12in, Width = 5in, Height = 11in, THK = 0.25” Polycarbonate material) (Figure 4-2)
2. Humidity Sensor
3. Temperature Sensor
4. Corrosion Sensor
5. LAN Cables and Hubs
6. PC with Lantronix Device Installer
7. Corrosion Classification Coupons
8. Sulfur

9. Petra Dish/Beaker
10. Electric Heater
11. Environmental Chamber

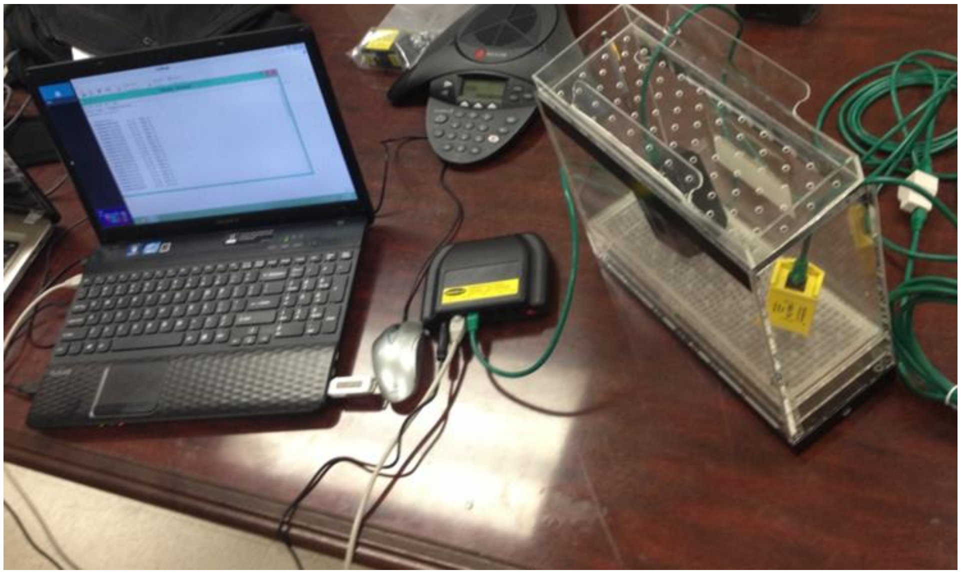


Figure 4-2: Bench Testing of Sensors

The temperature sensor and RH sensor data are captured in voltages and converted to their respective unit i.e. degree Celsius and percentage. IBM provided the patent owners of the sensors the conversion table.

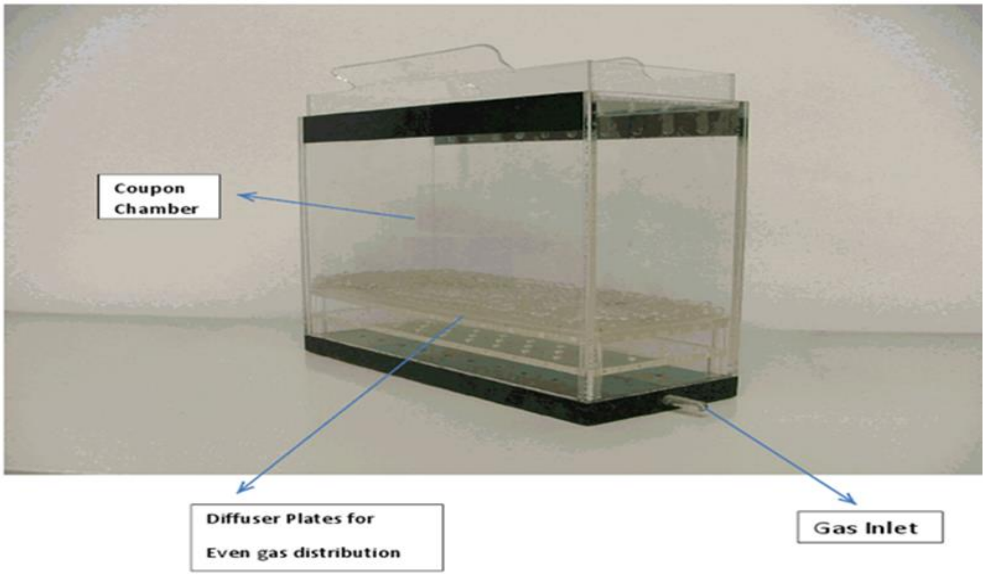


Figure 4-3: Corrosion Chamber

In figure 4-3 above shows the corrosion chamber with gas inlet at the base through a diffuser plate for even distribution of gases into the chamber. The coupons silver and copper shown in figure 4-4 below were carefully stored in a plastic cap to avoid any contamination before installation.

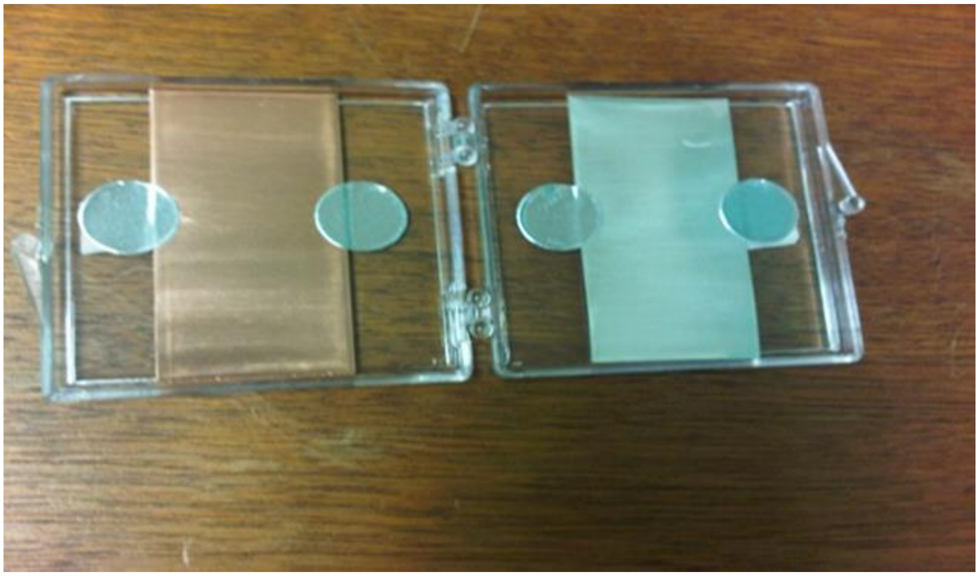


Figure 4-4: Corrosion Classification Coupon (CCC)

The sensors are connected through a series of LAN cables via the hubs to the PC. The PC has Lantronix software to gather data from the sensors (Humidity, Corrosion and Temperature), which are then converted, to the appropriate values.

Obtain a specific concentration of gas

After the bench testing the assembly is then placed inside the environmental chamber as shown in figure 4-3 above. In the second testing in order to create an environment with a known contaminants (i.e. Sulfur dioxide). A sulfur vapor concentration was created using flowers of sulfur (FOS) with the use of two reactants. The first reactant, pure sulfur flakes, second reactant potassium nitrate, diluted in distilled water.

$$4KNO_3 + 5S \rightarrow 2K_2O + 2N_2 + 5SO_2 \tag{4-1}$$

The amount of sulfur concentration as a function of temperature is listed in the table 4-1 below. Each concentration in ppm is associated with a temperature required to produce a steady supply of sulfur vapor inside the chamber.

Table 4-1: Table Showing Sulfur Vapor Concentration versus Temperature

Temperature		**Vapor Pressure**	**S_8 Volume Concentration**
°C	**°F**	**(mm)**	**(ppm)**
50	122	2.00E-04	0.26
60	140	4.00E-04	0.53
70	158	1.00E-03	1.32
80	176	2.30E-03	3.03
90	194	4.90E-03	6.45
100	212	1.00E-02	13.16
110	230	2.10E-02	27.63
114.5	238.1	2.80E-02	36.84

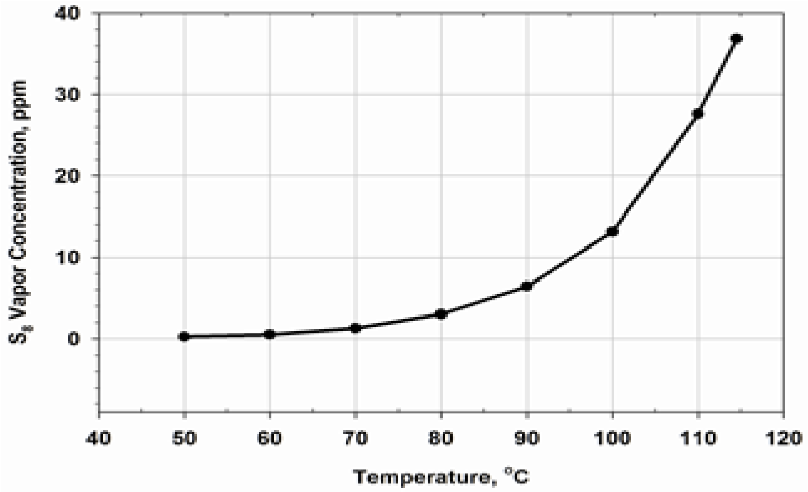


Figure 4-5: Graph Showing Sulfur Vapor Concentration versus Temperature

The vapor cloud is continuously maintained within the test chamber placed inside the environmental chamber while maintaining the temperature via the heater and the environmental chamber. Readings are taken every 30mins for Pressure, Temperature and Relative Humidity as well as corrosion and recorded via the Lantronix software on the connected PC. The corrosion chamber was then placed inside an environmental chamber, which makes it possible to provide airtight configuration within the corrosion chamber itself. It also provides constant temperature across the chamber. Temperature within the chamber builds up gradually and monitored via the temperature sensor. At the specified temperature vapors of SO2 begins to build up and creates a vapor cloud within the chamber continuously. With the humidifier also providing a means of moisture the experiment. This was maintained for 3days after which the data gathered over the period and the coupons where then removed for coulometric evaluation.

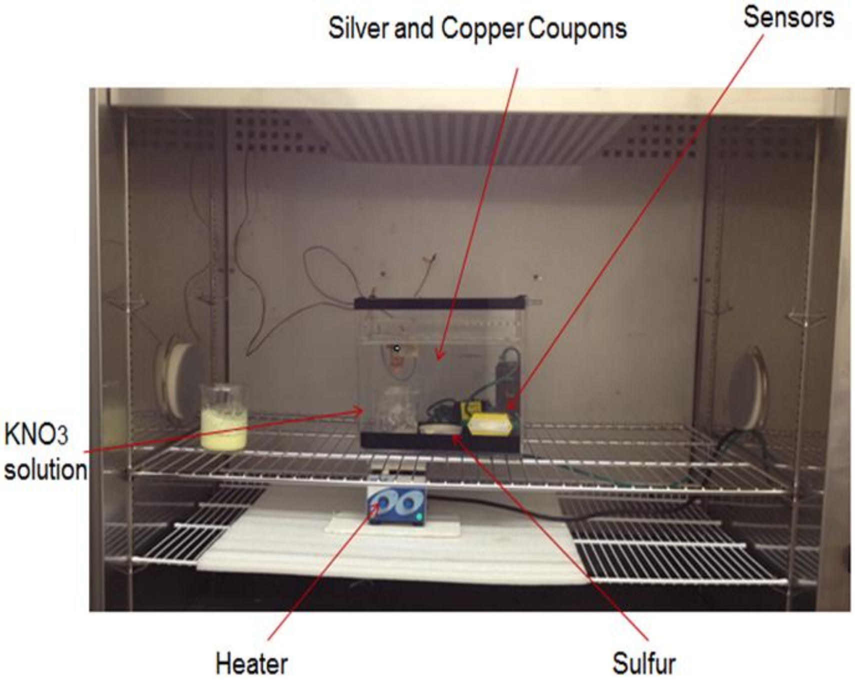


Figure 4-6: Environmental Chamber and Corrosion Chamber

4.1.2 Results and Discussions

After 72hours of exposure and readings taken every 30mins the result from the MMT Sensors shown below for corrosion, temperature and relative humidity. These results are obtained in voltages and then converted to their respective values by using IBM's patented conversion table. Over the period of exposure a total of 648 Angstrom and 502 Angstrom for Silver and copper corrosion product respectively were estimated to have been deposited. This was deposited from a gradual temperature increase from room temperature 28^{o}C to a maximum of about 45^{o}C from the heater maintained at about 50^{o}C.

Summary of experimental data for Temperature, RH and Pressure

Table 4-2: Excerpts of Raw data taken during the experiments

Time (hr.)	Temperature (^oC)	Relative Humidity (%)	Pressure (Pa)
59	40.69	37.84	0.623
60	41.78	41.44	0.623
61	42.44	41.44	0.623
60.5	42.75	39.8	0.623
64	43.09	39.15	0.623
65	43.28	37.51	0.623
65.5	45.69	43.74	0.623
66	45.66	42.1	0.623
66.5	45.53	42.76	0.623
67	45.69	42.76	0.623
67.5	45.56	43.08	0.623
68	45.56	41.44	0.623
68.5	45.56	45.05	0.623
69	45.56	44.07	0.623
69.5	45.59	42.76	0.623
70	45.53	42.43	0.623
70.5	45.59	43.08	0.623
71	45.53	42.76	0.623
71.5	45.59	42.43	0.623
72	45.5	28.98	0.623
72.5	45.5	32.75	0.623
73	45.54	32.75	0.623

The coupons analyzed by coulometric method after 3days of exposure in the chamber with the above environmental condition in a sequence described in section 3.1 above.

From the copper coupon, the following corrosion products as tabulated in table 4-3 below are copper oxides (CuO and Cu_2O), copper sulfides (Cu_2S) and silver sulfides. (Ag_2S). The total film thickness measured for copper corrosion is 658 Å and for silver corrosion is 648 Å. These are above the G1 severity level and fall in the G2 severity level. The coulometric/cathodic potential for CuO as shown in figure 4.7 below is between minus 0 – 600mV with an elapsed time of about 25s. For Cu_2O the coulometric/cathodic potential is minus 600 – 875mV with an elapsed time of 350s after the first corrosion product. For Copper sulfide (Cu_2S) the potential is between minus 900 – 1100mV with an elapsed time of about 650s.

Table 4-3: Corrosion product from Copper Coupon

Copper Corrosion Product	Seconds	Thickness of Corrosion product angstroms
Cu_2O	147	101
CuO	153	55
Cu_2S	615	502

For silver sulfide summarized in table 4-4 below; the coulometric/cathodic potential is between minus 700 – 1100mV with an elapsed time of about 750 seconds.

The coulometric for both corrosion products were in solutions of Potassium chloride (KCl).

Table 4-4: Corrosion product from Silver Coupon (CCC)

Silver Corrosion Product	Seconds	Thickness of Corrosion product angstroms
Ag_2S	667	648

In this experiment the oxides were only formed on the copper film and none on the silver film. This shows the sensitivity of copper to oxygen compared to silver.

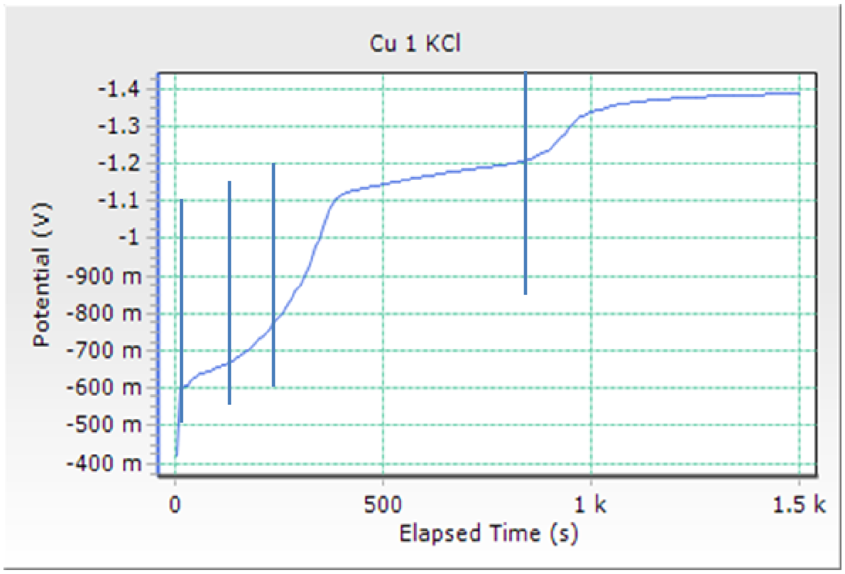


Figure 4-7; Plot of Potential versus elapsed time for Copper Corrosion product

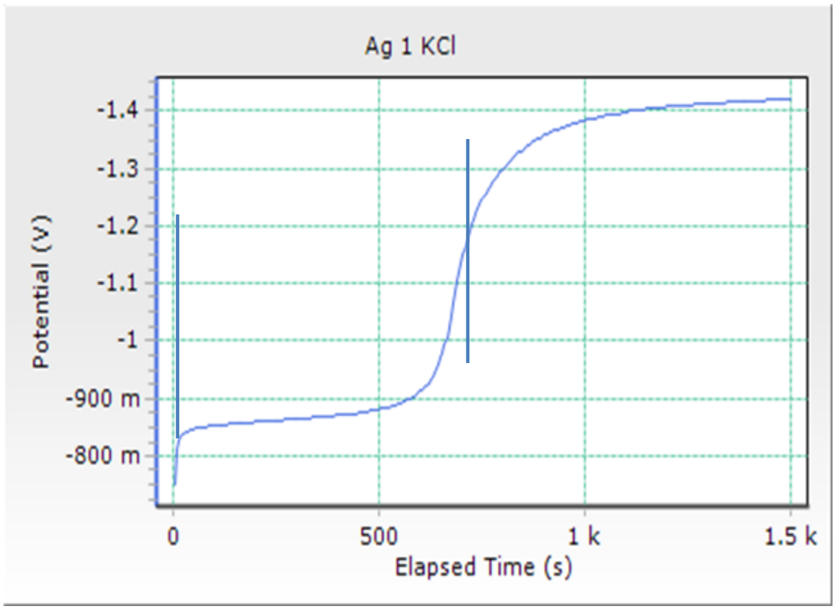


Figure 4-8: Plot of Potential versus elapsed time for Silver Corrosion product

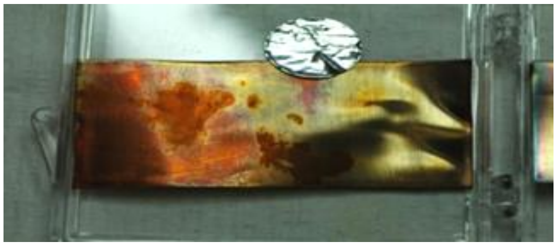


Figure 4-9: Exposed Copper Coupon after 72hours

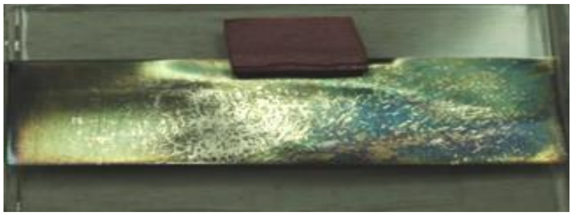


Figure 4-10: Exposed Silver Coupon after 72hours

Figures 4.9 and 4.10 are copper and silver coupons after 72 hours of exposure and the accumulated corrosion products at the end of 3-day testing period. The coulometric/cathodic potential of the product showed in the graphs indicates the potentials were the various products were reduced with the elapsed time. The corrosion stayed almost constant when the relative humidity was constant.

This is a model experiment required in the development of CFD code for the chemical reactions between Sulfur dioxide and Copper as well as Silver coupons. The corrosion thickness obtained 648 Angstrom over a period of 3days will be used in developing reaction kinetics of the reaction. In the development of the code an important parameter called Leonard Johnson energy potential (LJ) is required in the computation of the molecular dynamics. In this case the silver coupon will be used as it only reacted with Sulfur and therefore can be treated as a single equation. The reactants and products are not complex.

4.1.3 Modular Data Center

The Data center shown figures 4.11 and 4.12 below is a research data center jointly owned by EMNSPC and Mestex industries. It is located in an industrial environment in Dallas Texas. It uses air-side economizer with direct and indirect evaporative cooling. The entire unit consists cooling unit, cold air supply ducts, hot air exhaust/return duct, IT pod and I/DEC cooling Unit. The IT pod consists of 8 racks with servers, PDU’s, UPS’s, storage devices. The size of the IT pod itself is 10ft x 12ft x 28ft.

IT Pod Configurations

- Size: 126in X 85.5in
- IT Equipment: HP SE 1120 Servers (120 Servers)
- Cabinet: S6212B PANDUIT Rack
- Flow Provisioning: End inlet and Outlet configuration
- Inlet Dimensions: 13X27 vent with 45^o Louver Angle
- Outlet dimensions: 13X27

The data center is equipped with MERV 11 to filter continuously particulates from outside air.

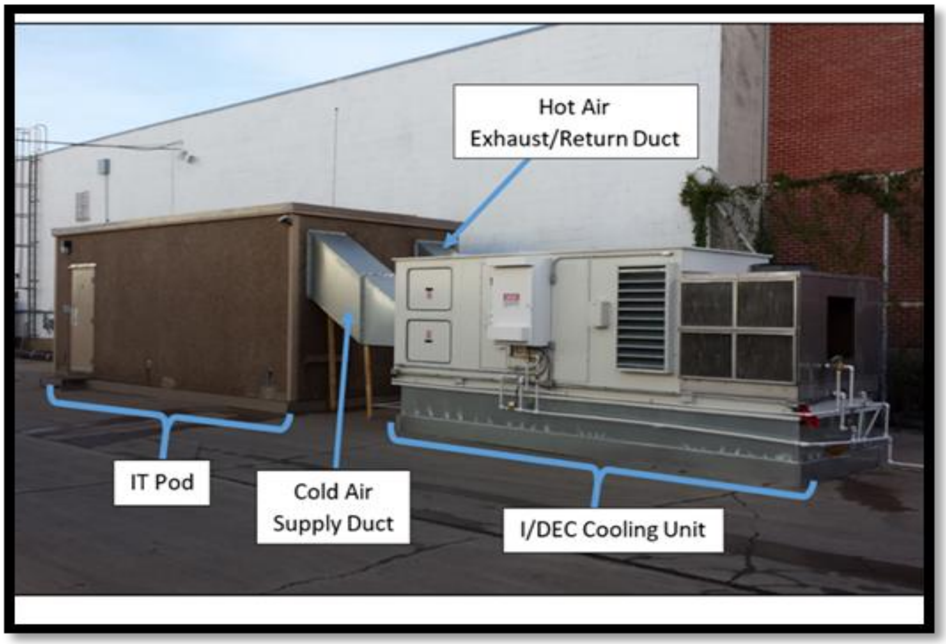


Figure 4-11: Research Modular Data Center [33]

Figure 4-12: Research Modular Data Center

Air enters through the supply duct into the cold aisle across the cabinet to cool the systems. Then hot air highlighted in figure 4.13 below is returned through the duct to the cooling unit outside the IT POD.

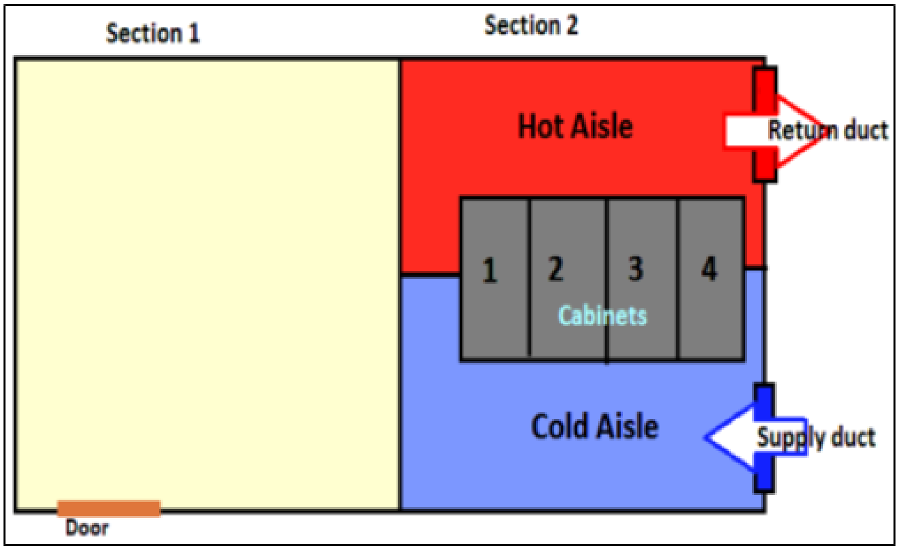


Figure 4-13: Layout of the IT POD showing air flow direction.

4.1.4 Severity Classification Testing of MDC

In order to classify the environmental condition of the location of the experimental data center coupons were placed at height locations ¼”, ¾” as specified in ASHRAE Datacom guidelines and as shown below. For this testing the coupons were placed facing the incoming air into the rack. The coupons were also adjusted slightly for adequate airflow into the rack impact when entering the rack. Dead air flow spot were avoided. At the locations shown in figure 39 below the coupons were left for 30days. This experiment is particularly important to determine the severity of the located data center.

Figure 4-14: Corrosion Classification Coupon (CCC)

After one month of exposure the coupons were then removed for coulometric/cathodic evaluation.

4.1.5 Results of Copper Coupon 1 (1/4”)

From copper coupon 1, placed at ¼” height the following corrosion product as tabulated in below are copper oxides (CuO and Cu_2O), copper sulfides (Cu_2S). The total film thickness measured for copper corrosion is 102 Å at this location. This is within the G1 severity level. The coulometric/cathodic potential for CuO as shown in figure 4-15 below is between minus 0 – 600mV with an elapsed time of about 94s. For Cu_2O the coulometric/cathodic potential is minus 600 – 775mV with an elapsed time of 68s after the first corrosion product. No Copper sulfide (Cu_2S) was formed with the corrosion product. A couple reasons might be responsible for it to be investigated in future evaluation. One thing that readily jumps out is the fact that the environment with the operating conditions might not have been sufficient for the reaction to occur.

Table 4-5: Copper Coupon 1

Coupon	Copper Corrosion Product	Seconds	Thickness of Corrosion product angstroms	Exposure days	Copper Corrosion rate, angstrom/month
1 /4 height	Cu_2O	98	68	30	102
	CuO	94	34		
	Cu_2S	0	0		

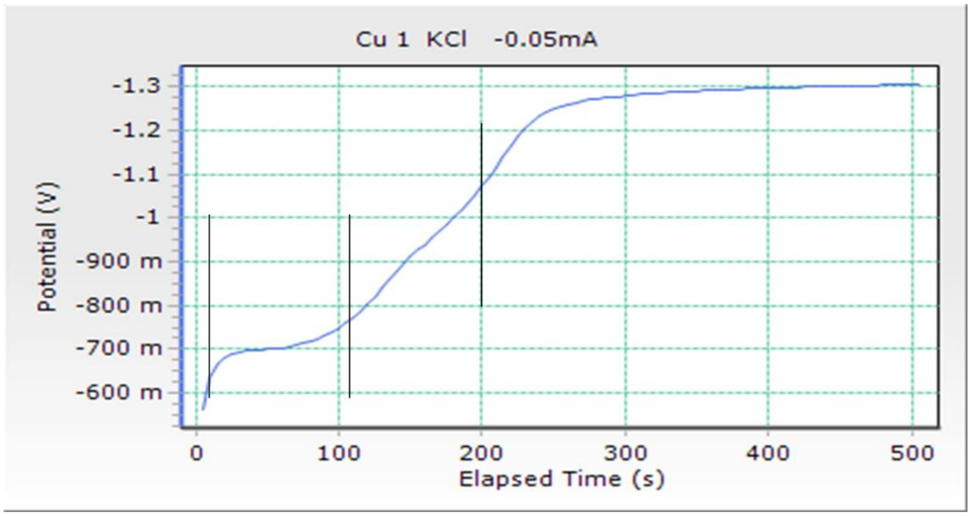


Figure 4-15: Plot of Coulometric/Cathodic Reduction for Copper Coupon 1

4.1.6 Results of Copper Coupon 2 (3/4”)

For copper coupon 2, placed at 3/4” height the following corrosion product as tabulated in below are copper oxides (CuO and Cu_2O), copper sulfides (Cu_2S). The total film thickness measured for copper corrosion is 122 Å at this location. This is within the G1 severity level.

The coulometric/cathodic potential for CuO as shown in figure 4-16 below is between minus 0 – 600mV with an elapsed time of about 83s. For Cu_2O the coulometric/cathodic potential is minus 600 – 790mV with an elapsed time of 133s after the first corrosion product. Again like the first copper coupon no Copper sulfide (Cu_2S) was formed with the corrosion product.

Table 4-6: Copper Coupon 2

Coupon	Copper Corrosion Product	Seconds	Thickness of Corrosion product angstroms	Exposure days	Copper Corrosion rate, angstrom/month
3 /4 height	Cu_2O	133	92	30	122
	CuO	83	30		
	Cu_2S	0			

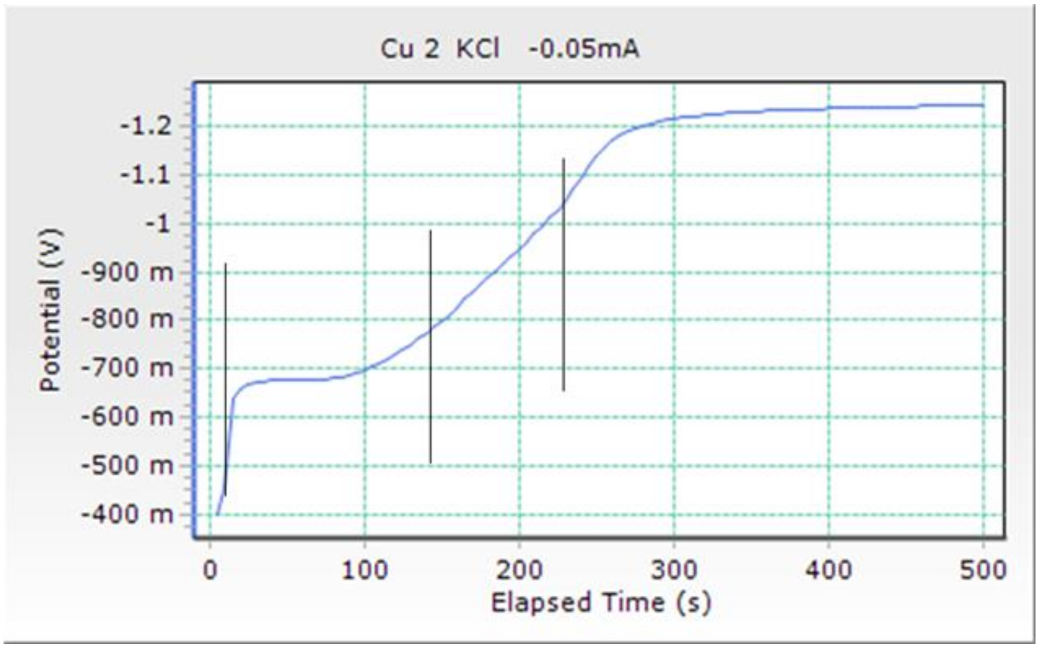


Figure 4-16; Plot of Coulometric/Cathodic Reduction for Copper Coupon 2

4.1.7 Results of Silver Coupon 1 (1/4”)

For Silver coupon 1, placed at ¼” height the following corrosion product as tabulated in Table below only silver sulfides (Ag_2S). The total film thickness measured for silver corrosion is 363 Å at this location. This is in the G2 severity level. The coulometric/cathodic potential for CuO as shown in figure 42 below is between minus 0 – 800mV with an elapsed time of about 373s.

Table 4-7: Silver Coupon 1

Coupon	Silver Corrosion Product	Seconds	Thickness of Corrosion product angstroms	Exposure days	Silver Corrosion rate, angstrom/month
1 /4 height	Ag_2S	373	363	30	363

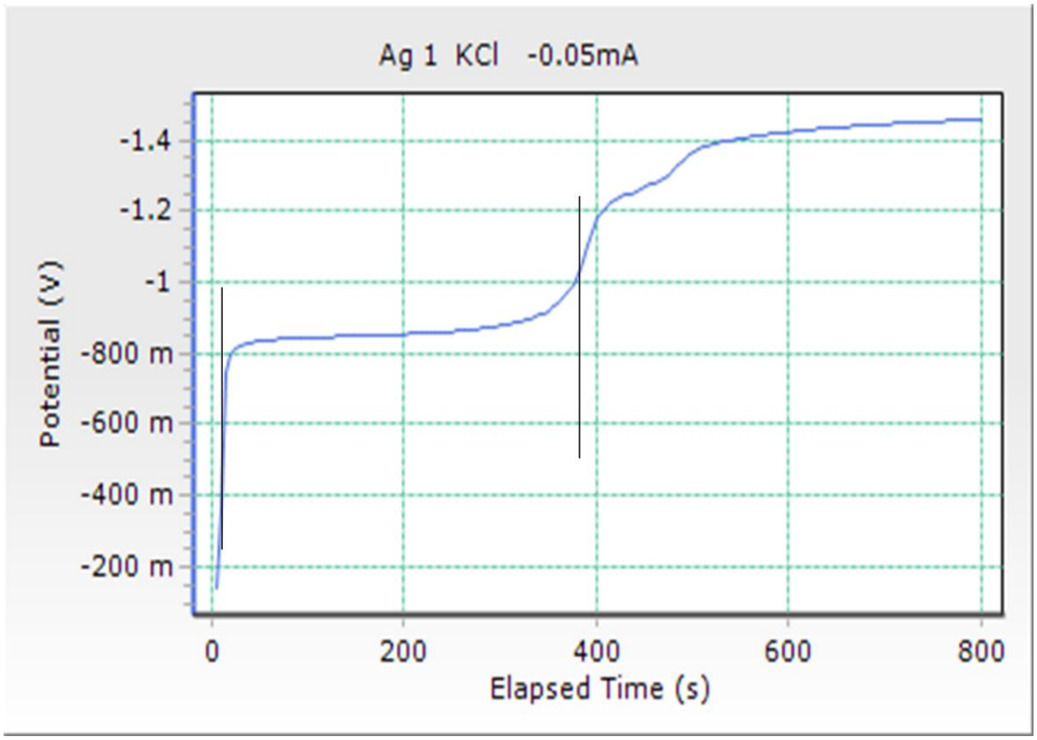


Figure 4-17; Plot of Coulometric/Cathodic Reduction for Silver Coupon 1

4.1.8 Results of Silver Coupon 2 (3/4”)

For Silver coupon 2, placed at 3/4” height the following corrosion product as tabulated in Table below only silver sulfides (Ag_2S). The total film thickness measured for silver corrosion is 233 Å at this location. This is in the G2 severity level. The coulometric/cathodic potential for CuO as shown in figure 4-18 below is between minus 0 – 800mV with an elapsed time of about 240s.

Table 4-8: Silver Coupon 2

Coupon	Silver Corrosion Product	Seconds	Thickness of Corrosion product angstroms	Exposure days	Silver Corrosion rate, angstrom/month
3 /4 height	Ag_2S	240	233	30	233

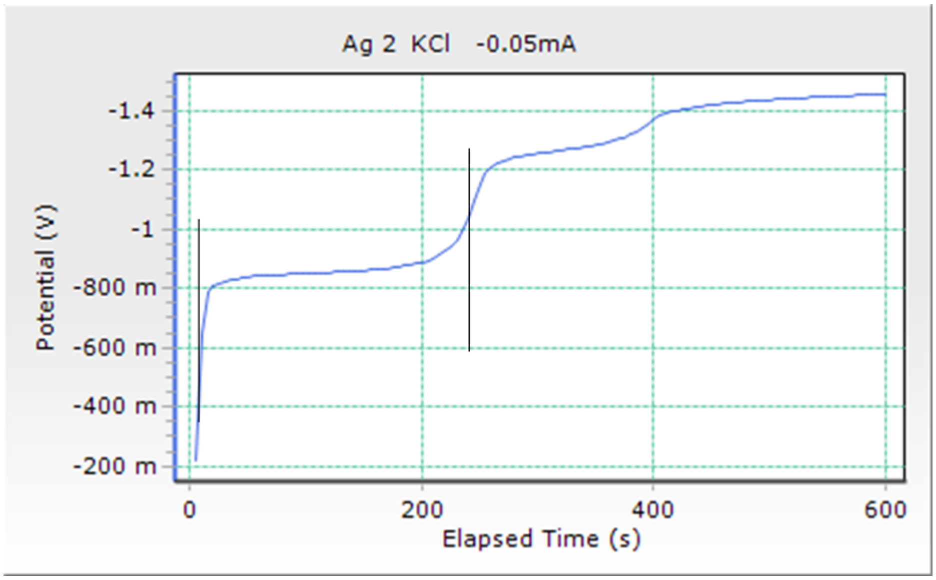


Figure 4-18: Plot of Coulometric/Cathodic Reduction for Silver Coupon 2

4.1.9 Discussions

From the above results and observations, the silver coupons has the highest corrosion thickness during the entire exposure at both locations. In the coulometric/cathodic reduction current densities used are 0.05mA for all the coupons. What is also intriguing is the fact that there was no copper sulfide on the corrosion thickness for both coupons. In the laboratory experiment with the sulfur environment copper sulfide accounted for the highest corrosion thickness.

The other hand as seen from the results only silver sulfide were formed on both locations. In classifying this environment the highest values of corrosion thickness are selected which are:

373 angstrom > 200 angstrom @ ¼" height similarly 273 angstrom > 200 angstrom @ ¾" height which suggests that MDC can be classified as G2 environment.

4.2 Run to Failure Testing or 4320 hours

The next step was to evaluate the performance of IT components in this environment. This is conducted while the data center is in operation. To set this up appropriately for a continuous data gathering and monitoring. RF Wireless code sensors shown Fig 4-19 below was installed at several location at both the cold and hot aisle. RF wireless code is a wireless environmental monitoring device used to environmental monitoring within data center. It removes the problem or investment cost or using hardwire to monitor the condition within data center. Each RF code is installed with a unique ID number to obtain relative humidity and temperature at the installed location. This information is then sent to Lab view set up on a laptop for monitoring purposes. The RF codes are equipped with batteries that can last for over 3.5years.

4.2.1 Physical Environment; Temperature and Relative Humidity

In the run to failure testing for the period stated above 4360 hours i.e. 6months or failure of any reported component if it occurs. All data from RF code Temperature (dry and wet bulb) Relative humidity at inlet and outlet of the data center. Data at selected locations shown in Figure 4-20 below. Each of the cabinet has RF wireless code sensor with its own unique ID for easy classification and subsequent data analysis. Figure 4-19 below also shows views of the cold aisle and hot aisle from the door to the IT pod.

Figure 4-19: Corrosion Classification Coupon (CCC)

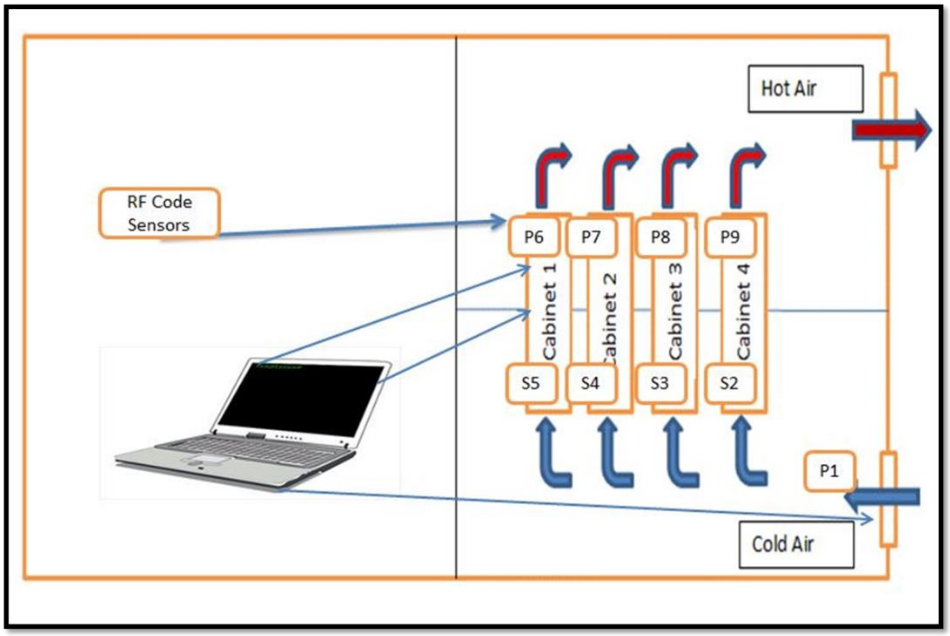


Figure 4-20: Corrosion Classification Coupon (CCC)

In parallel the physical environment of the IT was first classified in the works of [33] and summarized below.

The regions in figures 4-21 and 4-22 below shows regions of the cooling units (ASC-15-2A11) to bring outside air into the target regions; recommended or Class A1 allowable. For both charts, if outside air falls in Region 1, this cooling unit cannot be used to bring air into the target regions since it is outside air contains too much moisture. Therefore Dehumidifiers, DX cooling units, or multistage IEC units may need to be used. For all regions other than region 1, the cooling unit can be used to bring outside air into the target regions. Below is a summary of how this may be achieved if outside air falls in:

- *Region 2; mix hot return air with outside air*

- *Region 3: outside air directly*
- *Region 4: Either DEC or IEC can be used for the chart based on the recommended envelope but only DEC is guaranteed to work for chart based on Class A1 allowable envelope. It may be more efficient to use the I/DEC mode.*
- *Region 5: IEC needs to be used. It may be more efficient to use the I/DEC mode.*
- *Region 6: mix hot return air with outside air. It may be necessary to run the DEC section to add moisture*
- *Region 7: DEC needs to be used. It may be more efficient to use the I/DEC mode.*
- *Region 8: Both IEC and DEC need to be used.*

The various scenario summarized above are the operational guide in the operation of the experimental data center. This was plotted on the psychometric charts overlaid with the ASHRAE recommended and allowable regions.

This helps when collating and overlaying the data on the psychometric chart. It is worth nothing here that as results of the limitations of the cooling units the systems were not ran according to the guidelines.

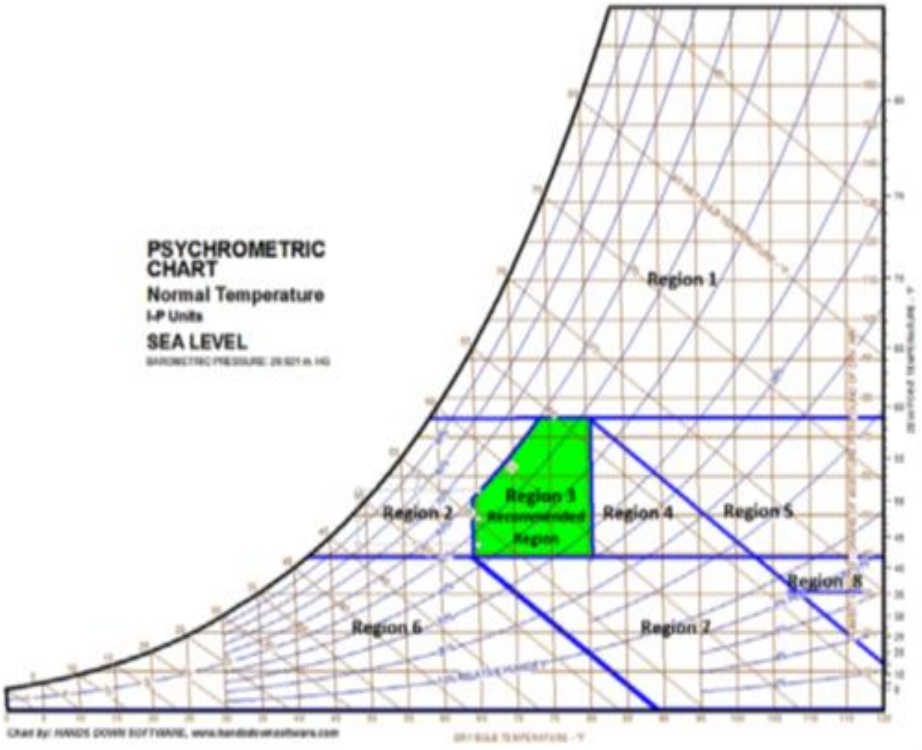


Figure 4-21: Data Bin for Various Regions-1

The data obtained are then placed in bins to allow plots on psychrometric charts software.

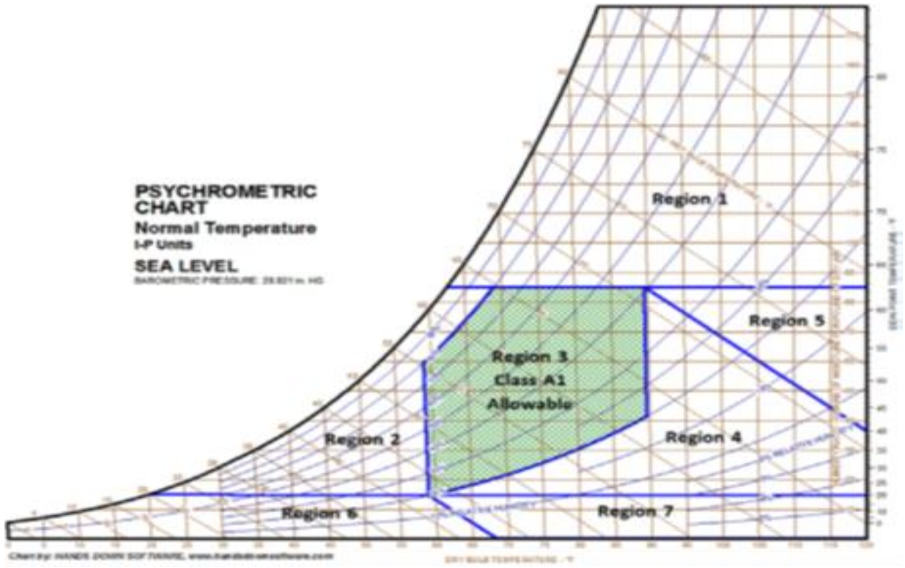


Figure 4-22: Data Bin for Various Regions-1

4.2.2 Results of Data Bins

For the data bins of obtained physical environment within the data center. In the month of April daily average were computed at the inlet i.e. sensor that was placed immediately after the inlet marked P1 in figure 4-20 above.

The same was collected for all the sensors at the cold aisle when they were functional and an average is computed to reflect the state of the cold aisle for the month of April.

This is then overlaid on the psychometric chart shown below.

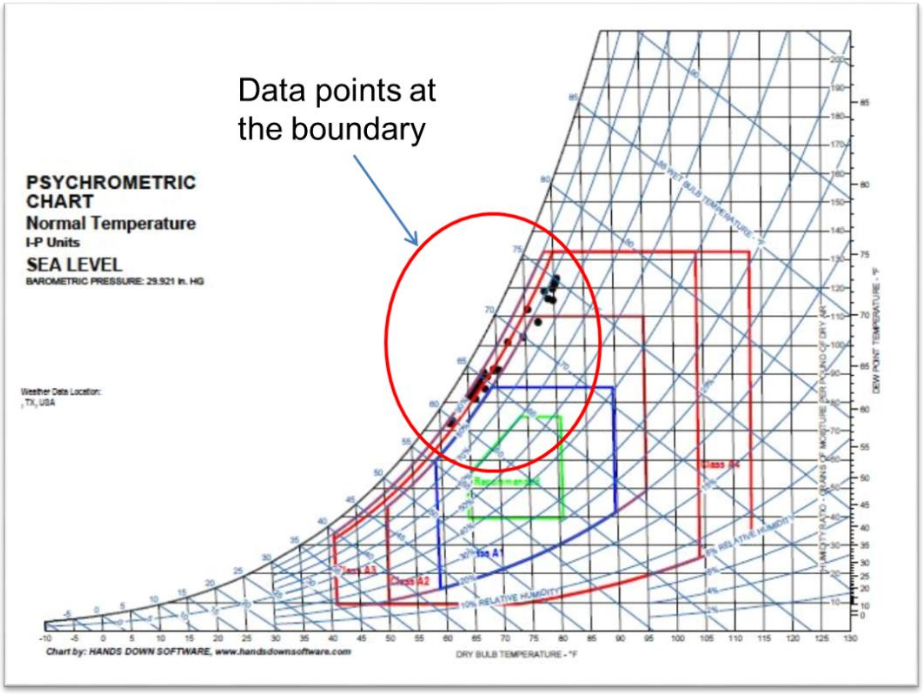
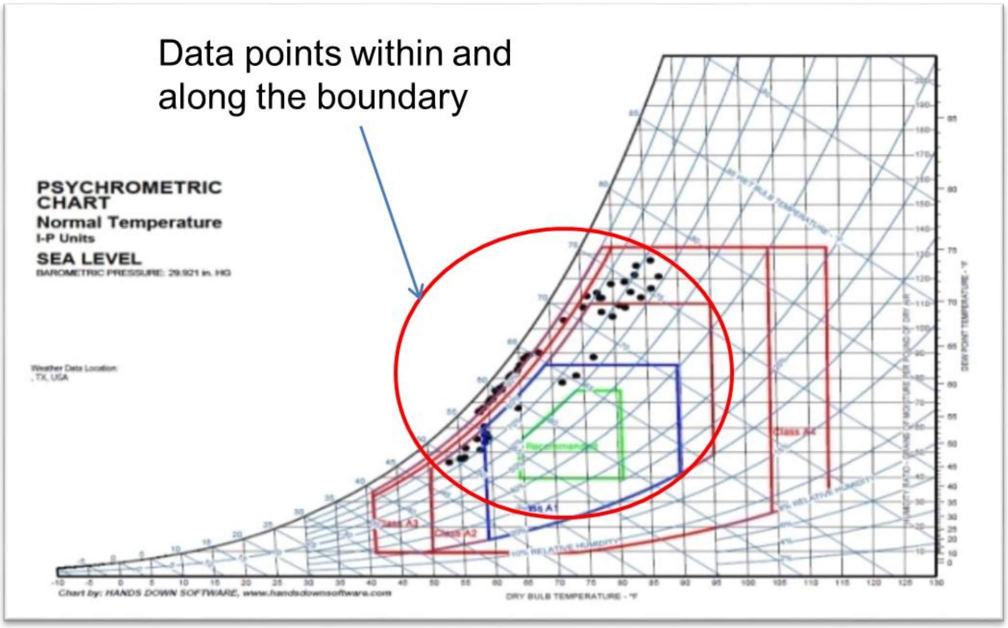


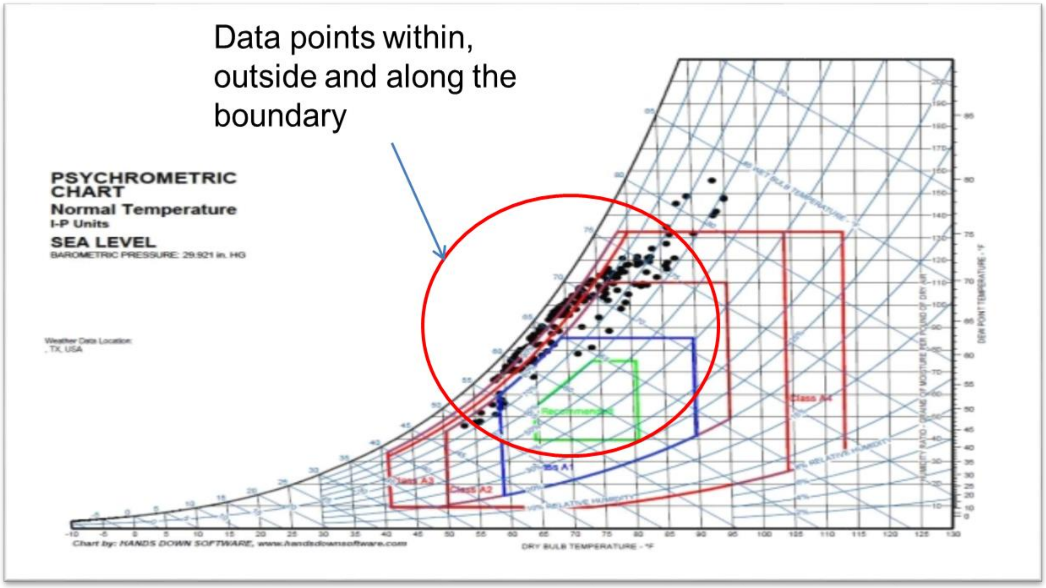
Figure 4-23: Data Bin for the Month of April

The same was computed for the months under investigation but only the months of April, May, June and July are reported below.



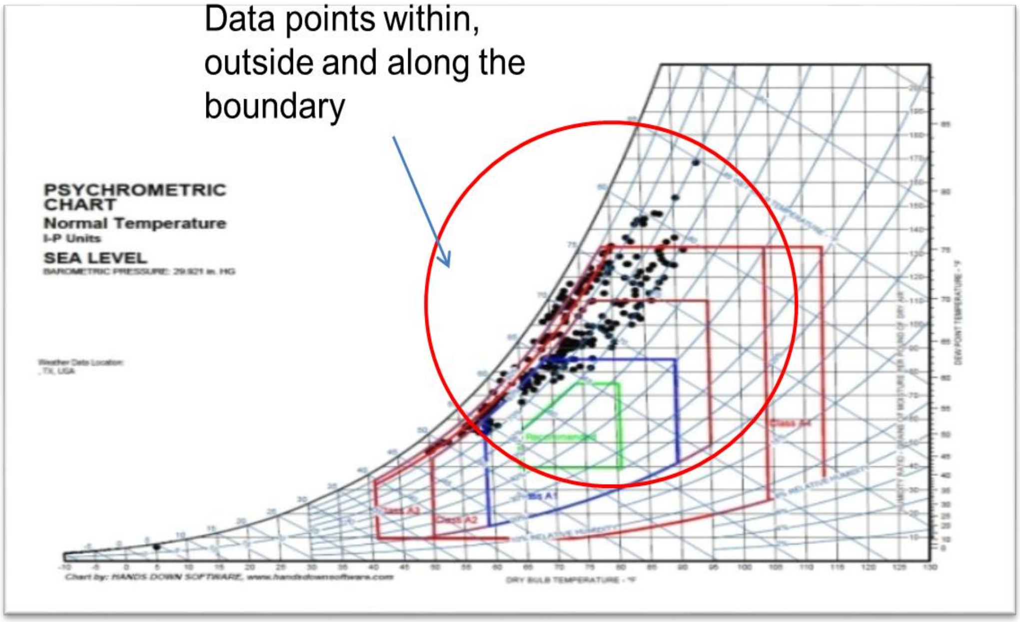
Data points within and along the boundary

Figure 4-24: Data Bin for the Month of May



Data points within, outside and along the boundary

Figure 4-25: Data Bin for the Month of June



Data points within, outside and along the boundary

Figure 4-26: Data Bin for the Month of July

4.2.3 Discussions of the Data Bins

From the above results, the physical environment for the months of April shows data completely outside the recommended ASHRAE envelope but within the recommended envelope of A2-A3. What we can learn from this is the fact that the environment itself for this month could have impacted the corrosion rates of the coupons. In the month of May the data recorded by the sensors and averaged across the aisle were at the boundary of regions A3 – A4 envelope. For the months of June and July Dallas is expected to have higher ambient temperature than previous months which was as seen in the figures 4-25 and 4-

26 notable excursions outside the recommended regions. This temperatures and relative humidity can further affect corrosion rates.

4.2.4. Results and Discussions of Run to Failure or 4320 hours

After 3622 hours of operation and ITE exposure there was a reported failure of two power density unit (PDU's) located in the hot aisle section of the IT pod. This was then removed and further examined as shown below. It is also worth noting that there were a total of 7 PDU's at the same location.

Table 4-9: Reported Failure at PDU

Total Exposed Duration (Hours)	Period
3622	05/30/2014 – 02/14/2016

Figures 4-27 and 4-28 below show the evaluated PDU's as compared with similar PDU used in a separate facility not exposed to outside air. It was discovered that the failure on both PDU's were not corrosion induced failure but rather an insulation failure. No corrosion products were observed on any of the two PDU's.

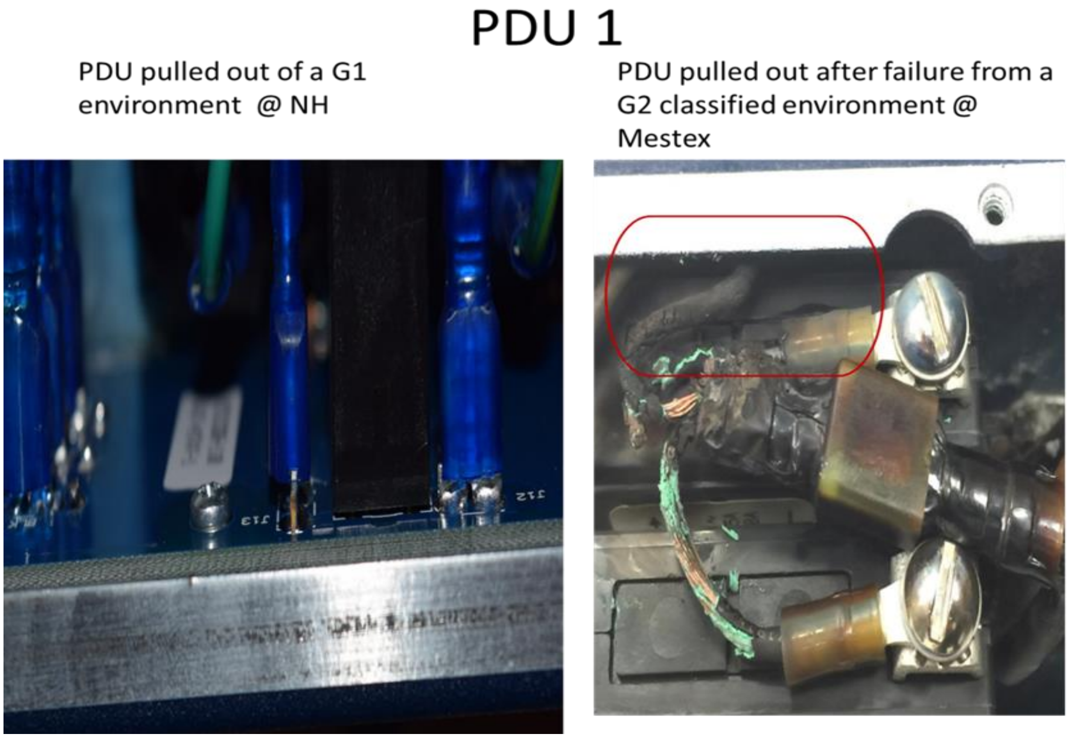


Figure 4-27: Failed Power Density Unit 1

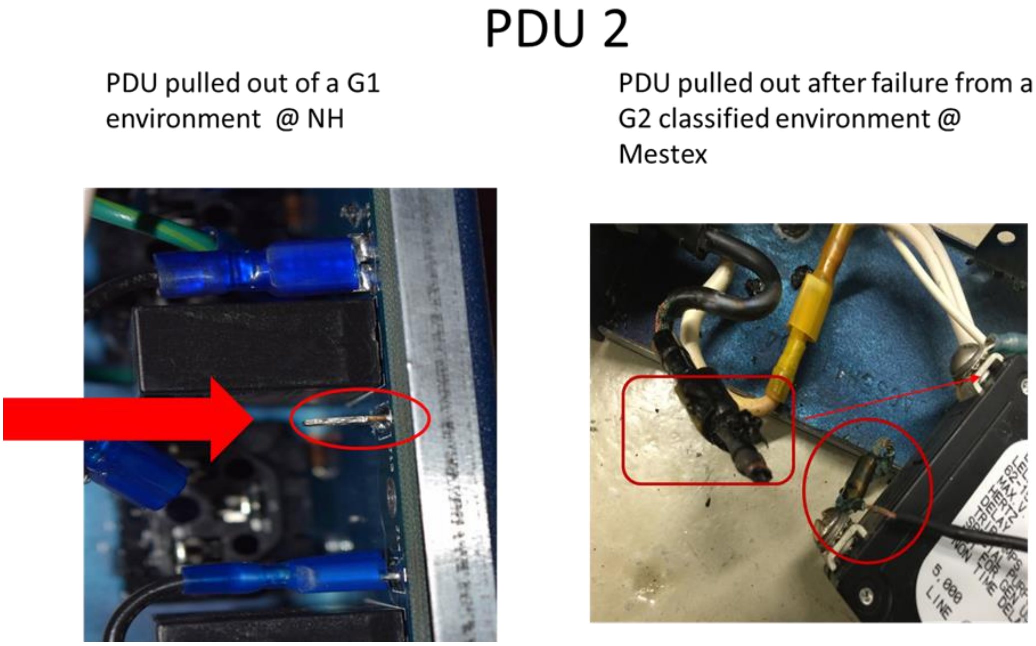


Figure 4-28: Failed Power Density Unit 2

In addition to the PDU's the following ITE's were also visually evaluated.

- Solder Points as shown below
- Resistors

From visual evaluation of the solder balls in comparisons with a similar one from another location shown in figure 4-29 below no indication of significant corrosion product at any of the surfaces. No microscopic evaluation was done at this time so that there will be no damage to the balls and render it unusable.

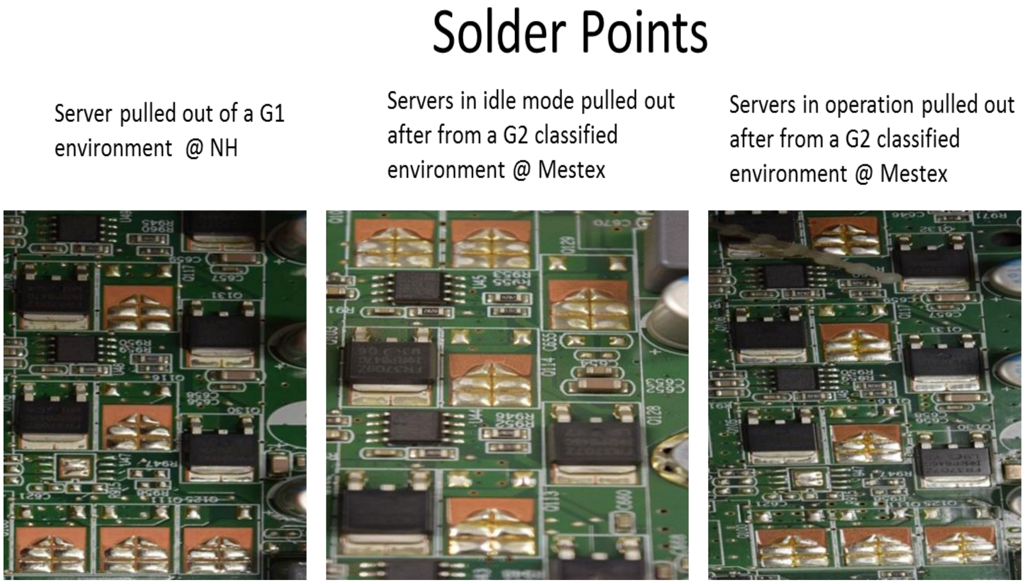


Figure 4-29: Solder Point on Electronic Equipment

Similarly inspected resistors at the connection points on PCB's did not show any corrosion product as no failure was reported. Previous reported experiment in harsh conditions show a failure of 500 hours [34] for resistors.

With the above data it is therefore possible to create a plot represented in the figure 4-30 below for ITE equipment for 4360 hours representing 6months.

Notable points of the curve are the indicated hours reported for resistors in harsh environment (i.e. 500hrs) afterwards are the PDU's reported failure although not corrosion induced failure. And finally on the line is the 6months (4320 hours) of exposure without any corrosion related failure in this classified G2 environment.

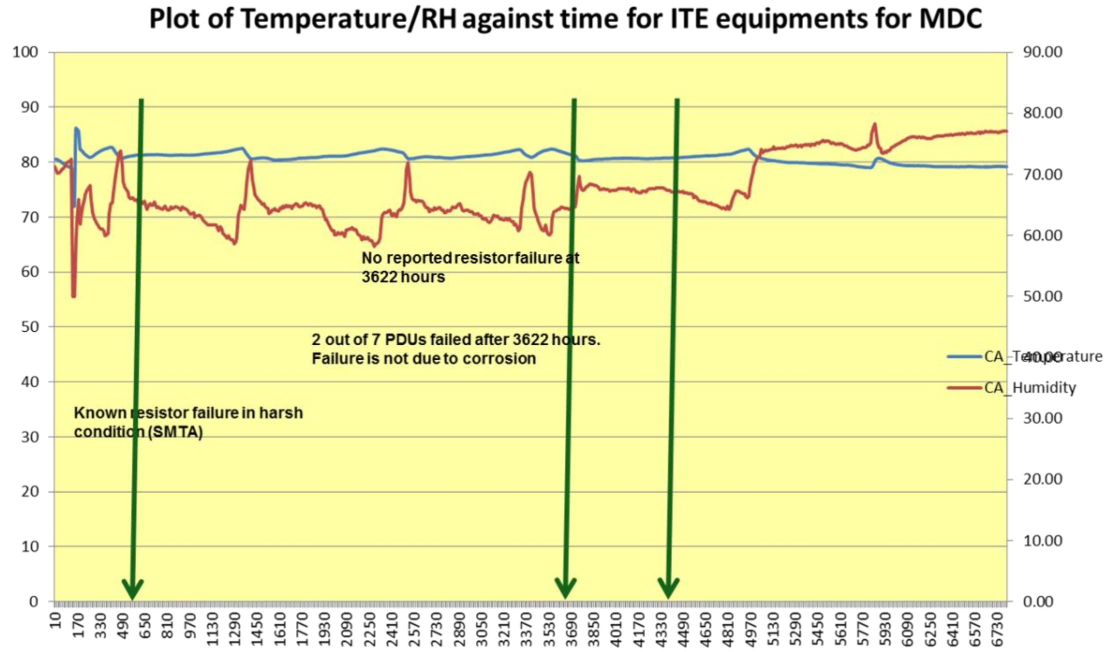


Figure 4-30: Hypothetical Plot of Equipment Reliability in a G2 Environment for duration of 4320 hours.

On the other hand is a likely plot of a G1 environment in figure 4-31 below where there were little or no pollutants in the data center operated separately at another location at University of Texas Arlington.

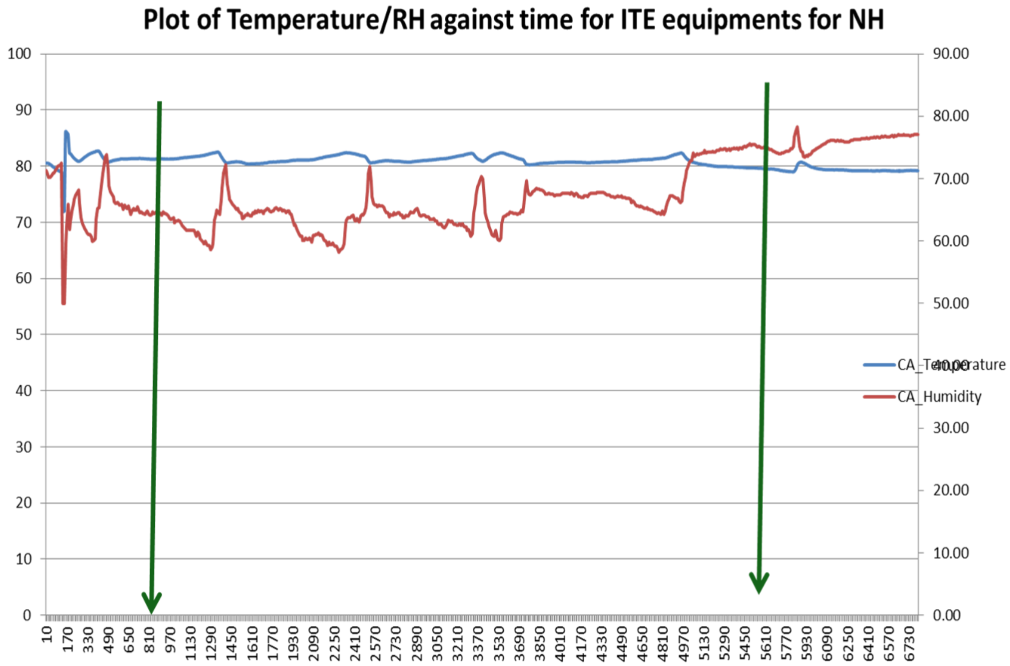


Figure 4-31: Hypothetical Plot of Equipment Reliability in a G1 Environment for a duration of 4320 hours.

Chapter 5

Conclusion

Based on the results of the above experiments it is quite unlikely that contaminants and moisture contributed to the failure of the PDU's. Also the fact that the other 5 PDU's (i.e. hot aisle) were did not fail and further evaluation of the failed components after 3622 hours of operation did not show any corrosion product.

During the entire duration of this exposure of ITE's in the data center there are no information to suggest that any of the evaluated component could fail due to contamination.

There were operating excursions (i.e. Temp and RH) outside ASHRAE envelope during this experiment but no impact was observed on the reliability of the ITE equipment.

It is therefore reasonable to infer that EE can safely perform reliably in a G2 environment for hours <5000hrs

In this experiment the IT pod was continuously filtered with ASHRAE MERV 11 so the impact of particulates was not evaluated and there was no dust aggregation on any of the equipment.

5.1. Future Work

In the experimental data center the classification was done for a single month. Looking at the activities within the industrial area it is highly unlikely that there will be consistent activities all year round. It is therefore expected that classification be carried out for all the months of the year. This will help to fully characterize the data center on a monthly basis help to understand duration of highest severity levels. Secondly as mentioned above, the data center was continuously filtered and hence no particulate effect was observed. It will be interesting to remove the filters and observe the effect of particulate as well. For the IT equipment that were visually evaluated we could not examine them microscopically as they have not failed. It is therefore important that after a failure microscopic evaluation must be performed on the failed components. It is also required to continue to run the data center until known corrosion related failure occurs. The data bin analysis should be continued to determine the percentages of excursions outside the envelope and durations of occurrence.

Other IT equipment component can also be installed (Storage, PCB's with different surface finishes) to understand their reliability in this environment

Appendix A.

Raw Physical Data

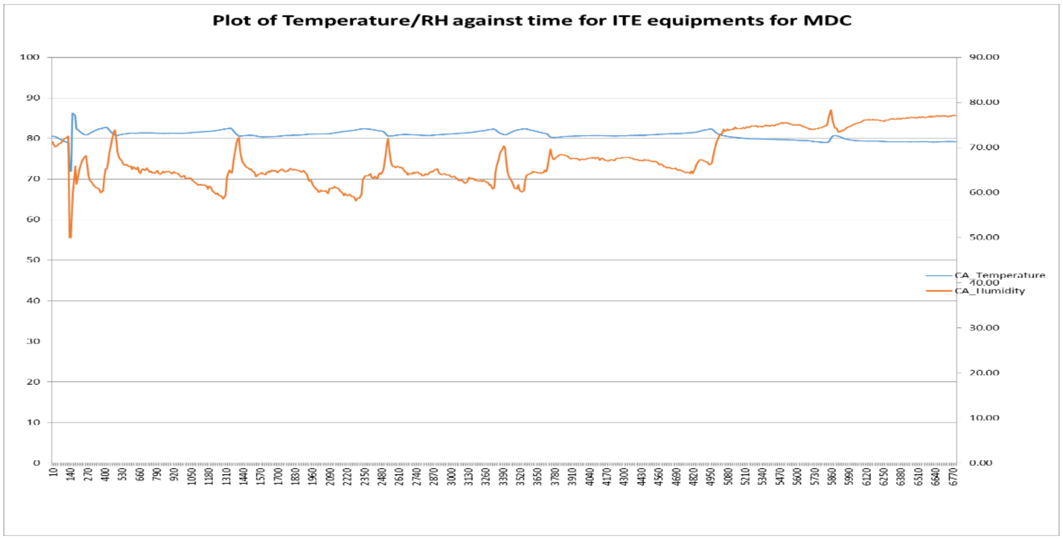


Figure A-1: Temperature and relative Humidity Data for 05/30

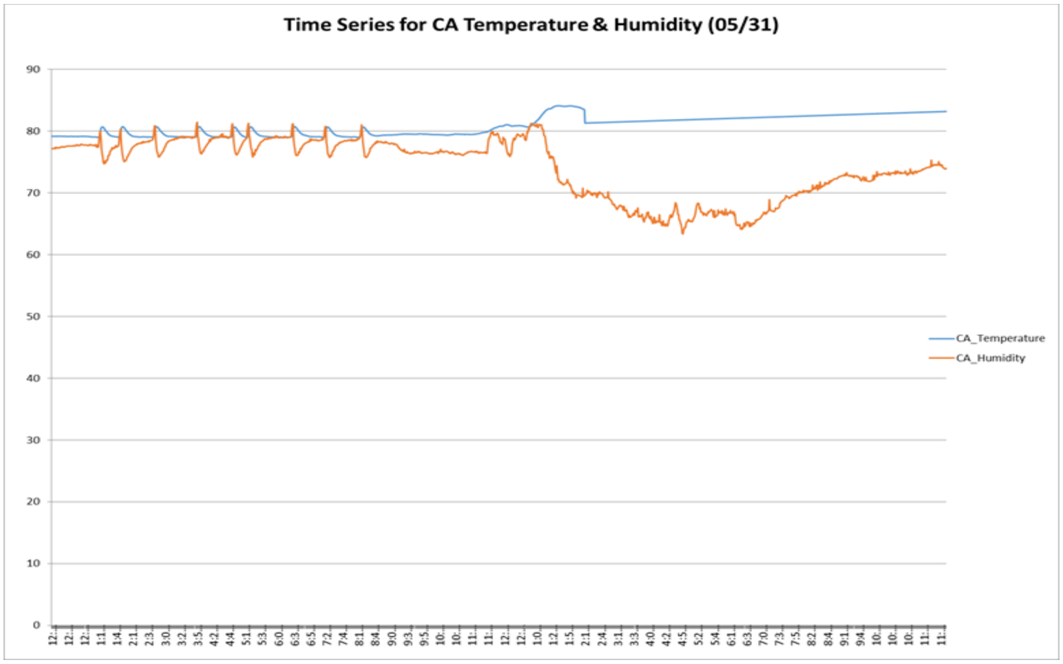


Figure A-2; Temperature and Relative Humidity Data for 05/31

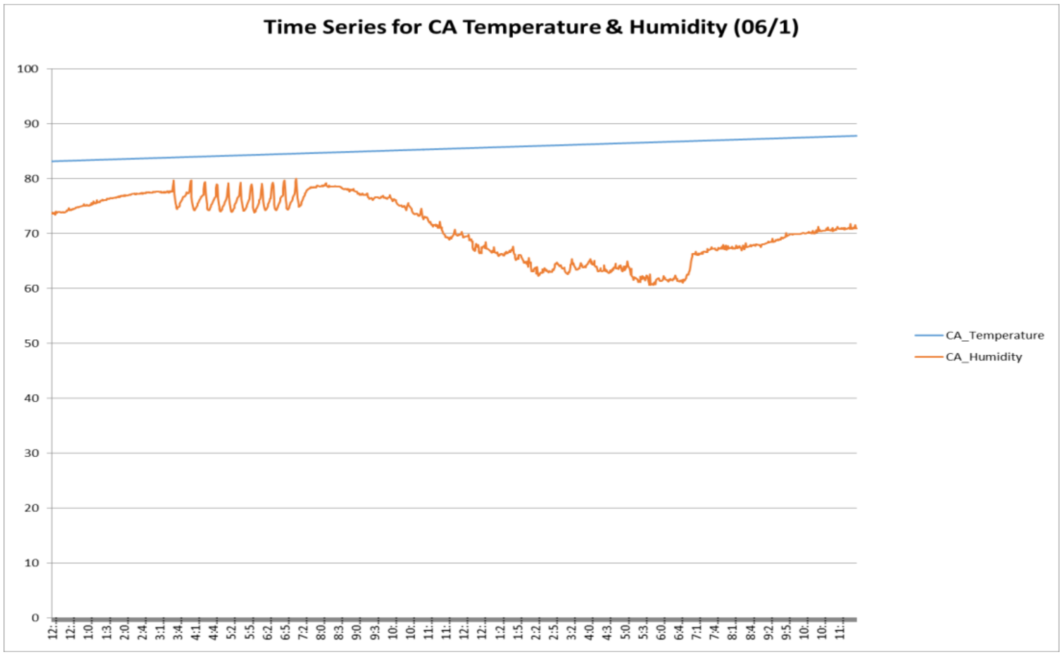


Figure A-3; Temperature and Relative Humidity Data for 06/01

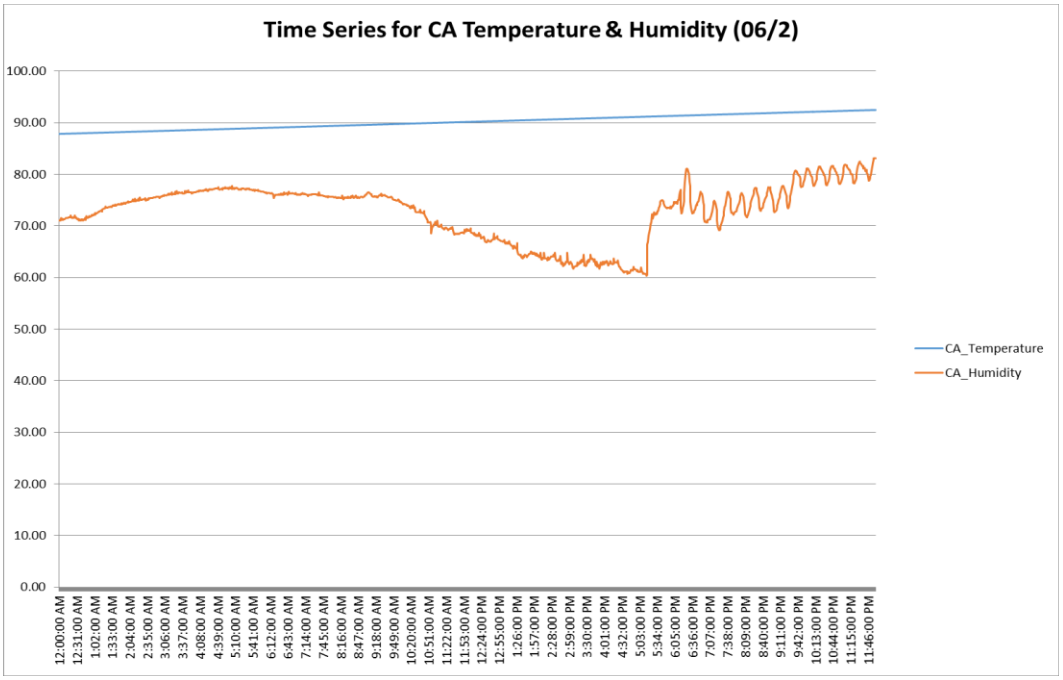


Figure A-4; Temperature and Relative Humidity Data for 06/02

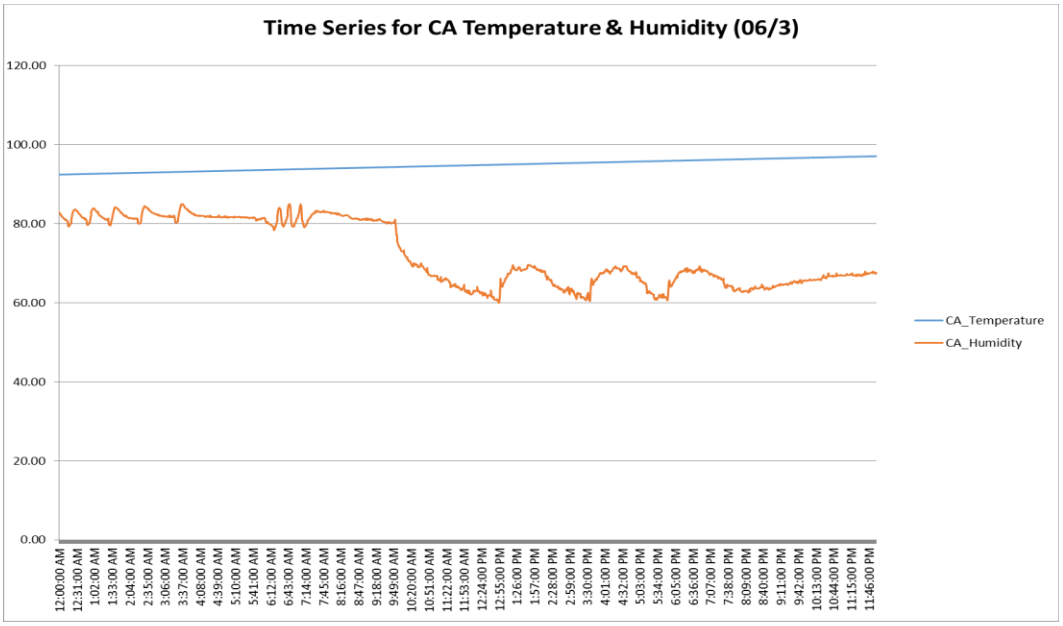


Figure A-5; Temperature and Relative Humidity Data for 06/03

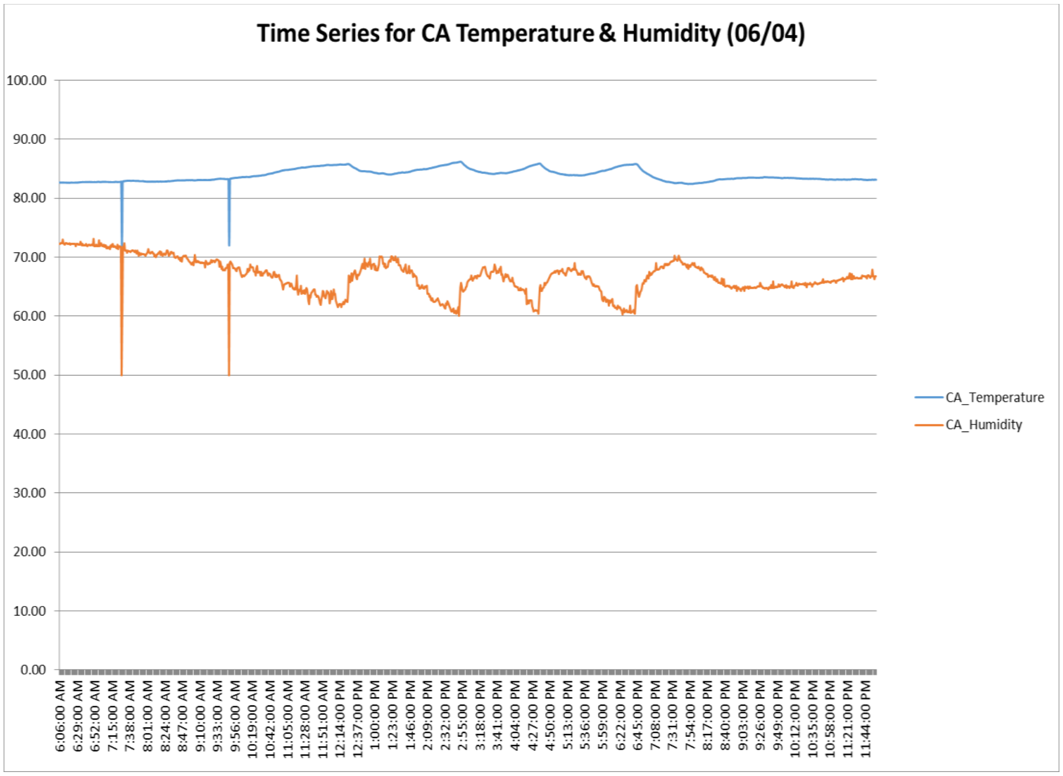


Figure A-6; Temperature and Relative Humidity Data for 06/04

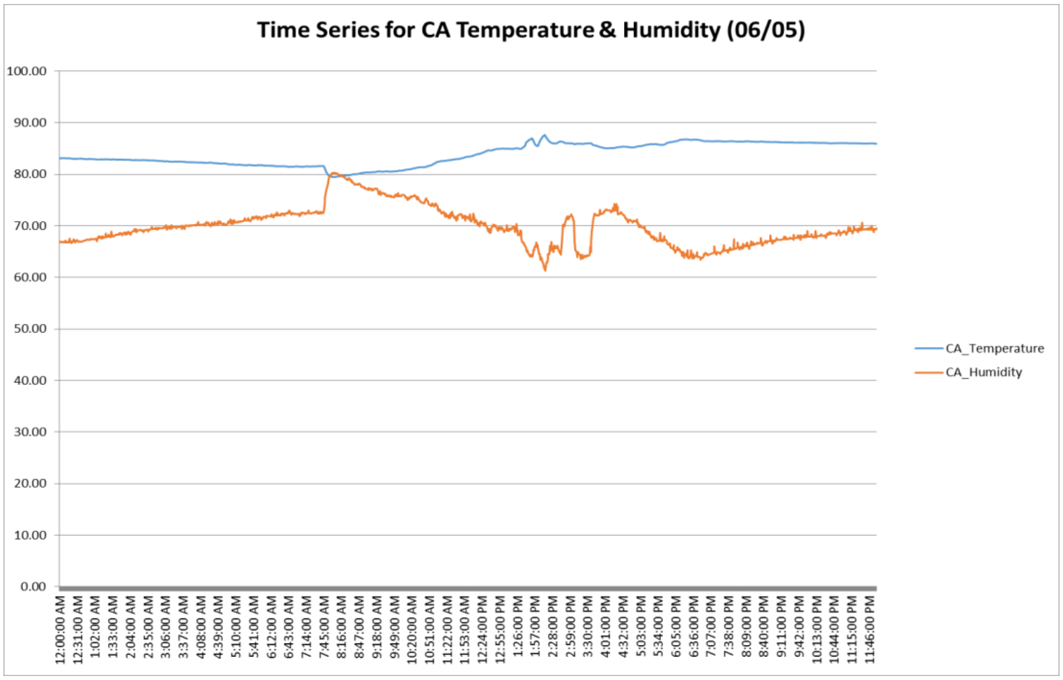


Figure A-7: Temperature and Relative Humidity Data for 06/05

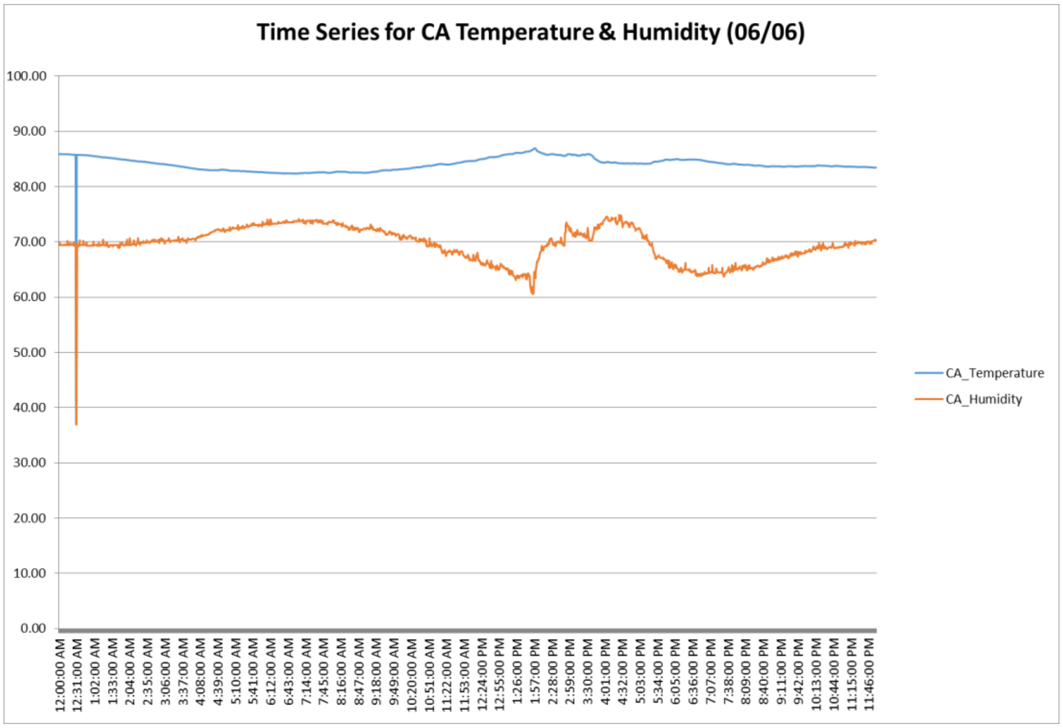


Figure A-8: Temperature and Relative Humidity Data for 06/06

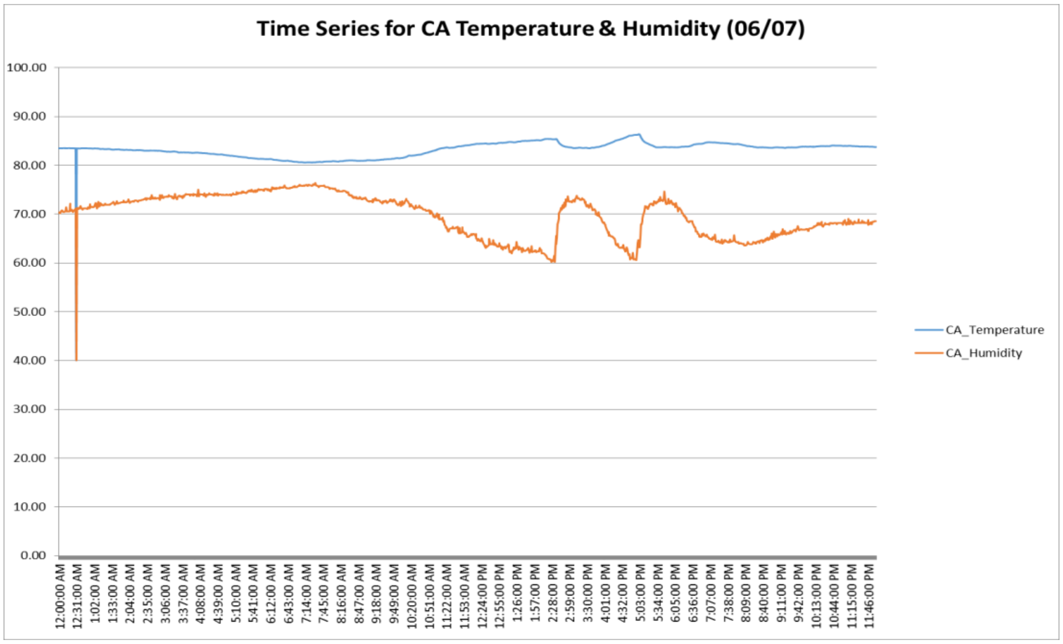


Figure A-9: Temperature and Relative Humidity Data for 06/07

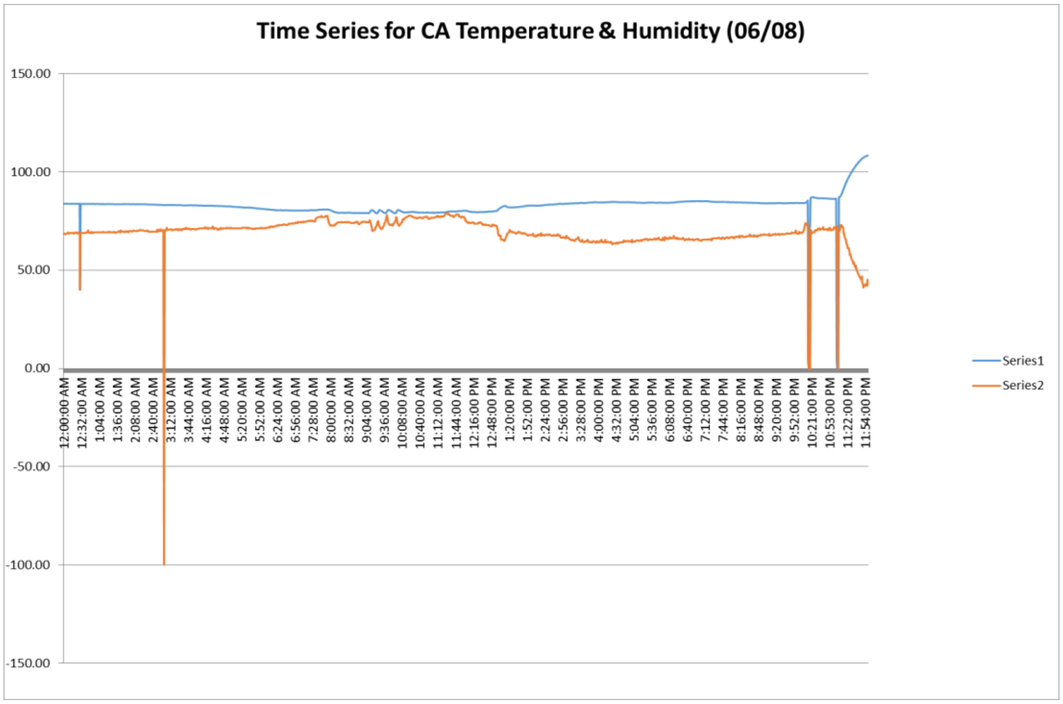


Figure A-10: Temperature and Relative Humidity Data for 06/08

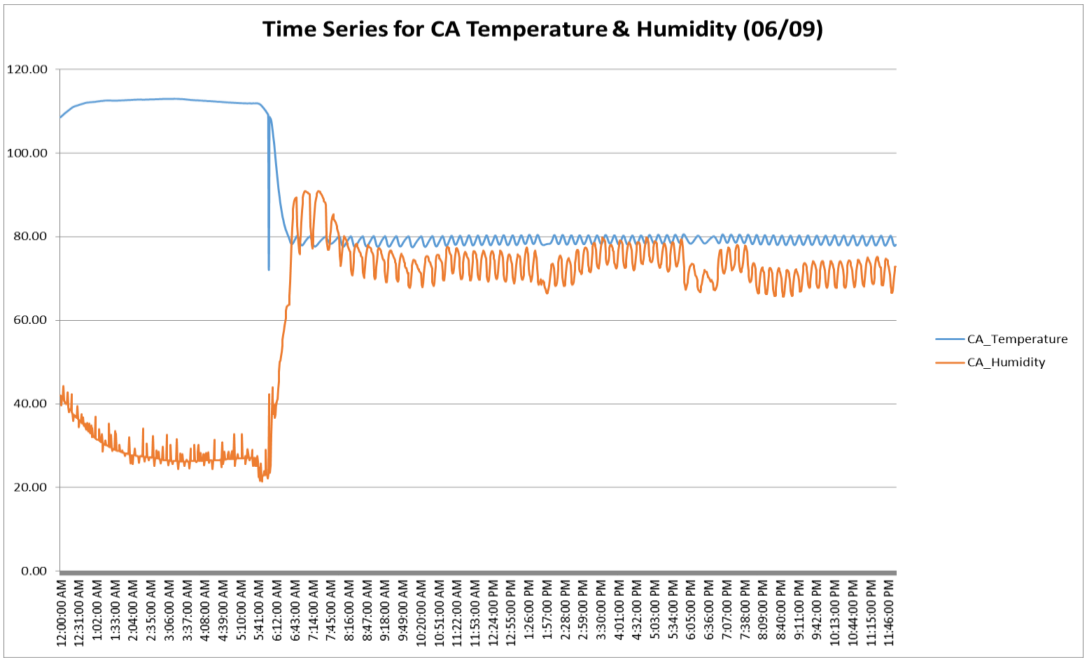


Figure A-11: Temperature and Relative Humidity Data for 06/09

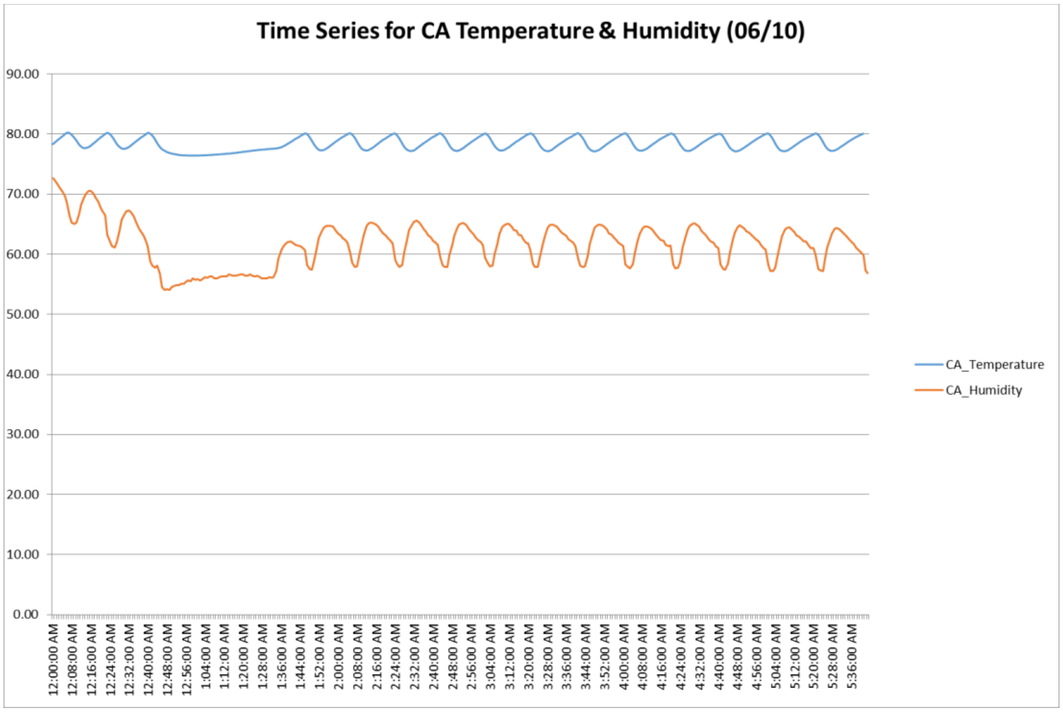


Figure A-12: Temperature and Relative Humidity Data for 06/10

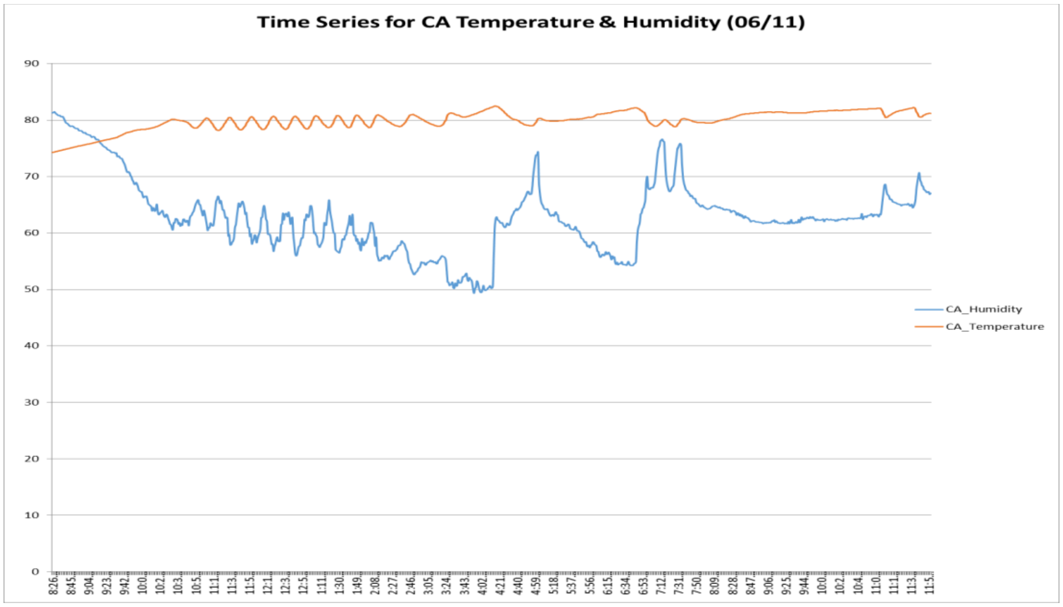


Figure A-13: Temperature and Relative Humidity Data for 06/11

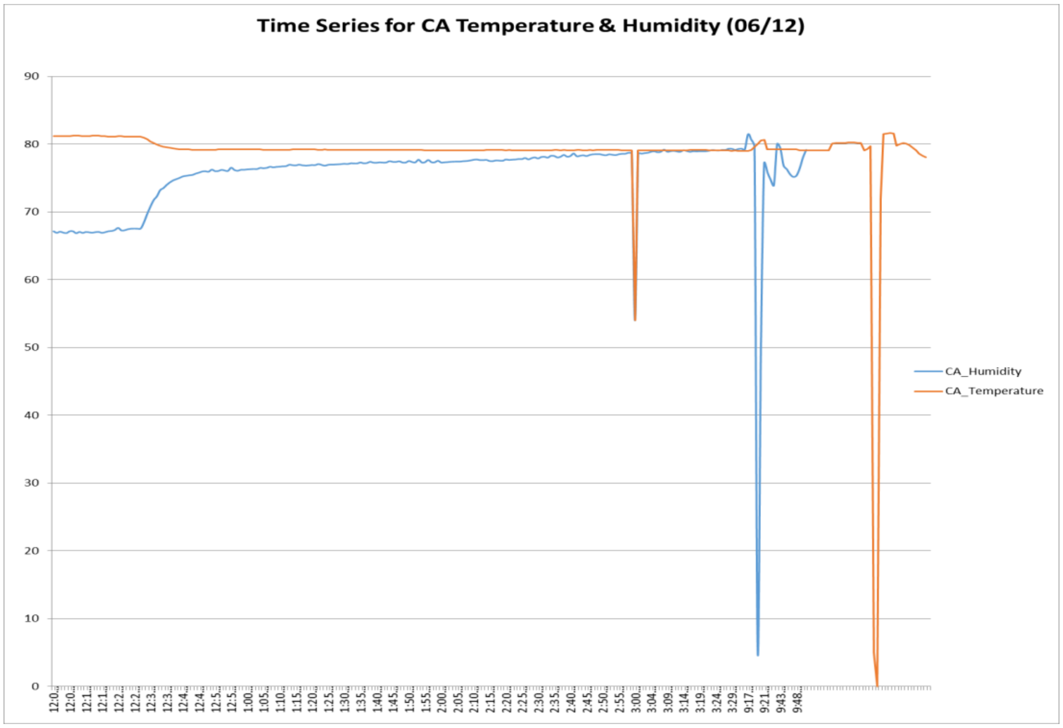


Figure A-14; Temperature and Relative Humidity Data for 06/12

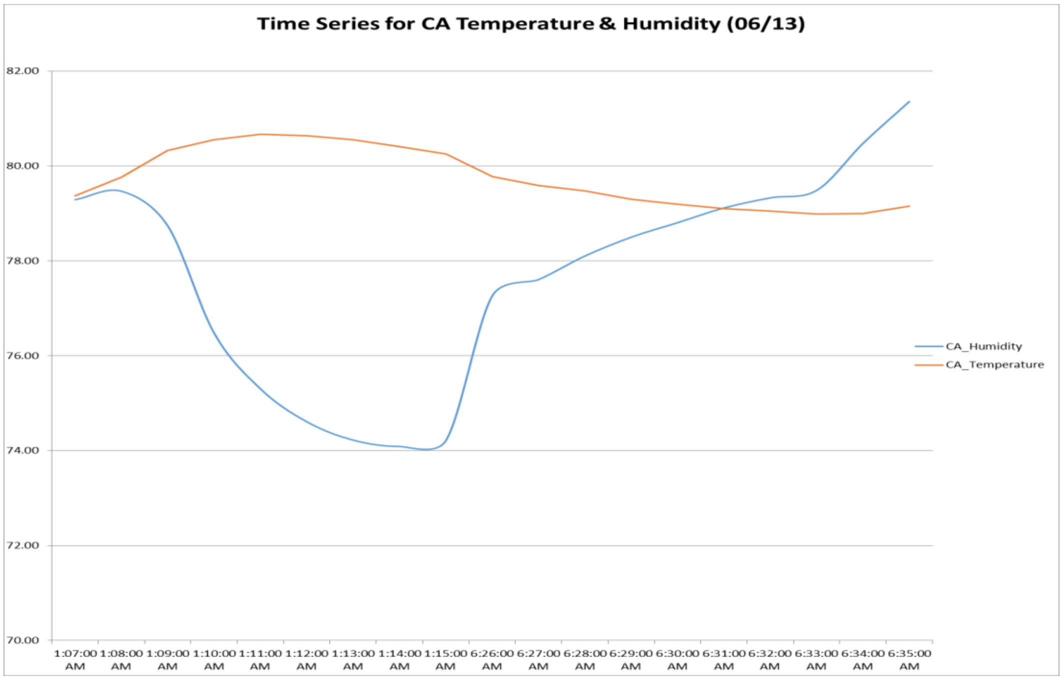


Figure A-15; Temperature and Relative Humidity Data for 06/13

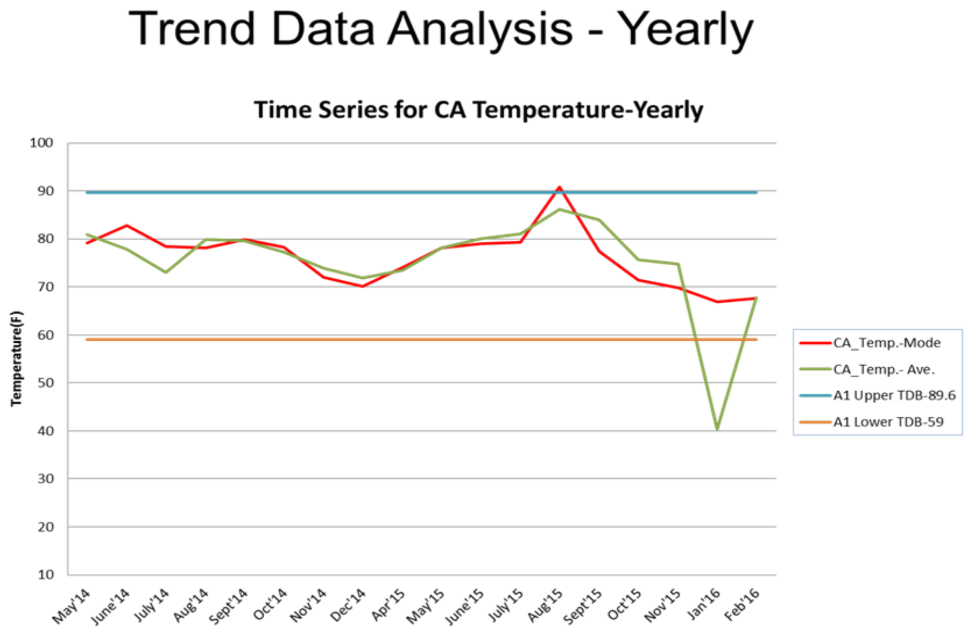


Figure A-16; Year Average Temperature and Relative Humidity Data

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Biographical Information

Oluwaseun Awe graduated with a Bachelor of Science and Masters of Science in Mechanical Engineering in August 1998 and May 2004 respectively from the University of Lagos Nigeria. He has worked after graduation in various capacity in the Energy Industry specifically the Oil and Gas. He is a high performing professional mechanical engineer with over 14years of postgraduate experience. He has specialist skills in pressure vessels, pipe stress analysis, equipment layout studies and finite element analysis of subsea equipment. He also has good working knowledge of heat exchangers, relief valves and piping systems. When he was at FMC Technologies he worked on a number of Finite Element Analysis project using ANSYS including fatigue assessment of top tension risers (TTR). He has managed the engineering of several gas plants including 150mmscfd Non Associated Gas NAG plant. In addition to his professional experience, he enjoys thermal analysis and HVAC designs.

Always eager to learn and take on new challenges and opportunities outside his area of expertise. One of the reasons he decided to join Dr. Dereje Agonafer’s EMNSPC team at University of Texas at Arlington. While he was with the team he joined a relatively new group involved in the contamination of data centers utilizing air-side economizer technology. He actively participated in all the activities within and outside his team and later lead the team in all experimental works in contamination.