IMPACT OF IMMERSION COOLING ON THERMO-MECHANICAL PROPERTIES OF NON-HALOGENATED CORE

BY

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Mohan Sai Ramalingam, MAY 2023

DEDICATION

I would like to dedicate my master’s dissertation

To

My parents

Pooja Ramalingam

Dr. Priya Bharathi

For their continuous support, love, and care towards me

And to my friend

Rohit Antony Raymonds

For his encouragement and support

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ABSTRACT

IMPACT OF IMMERSION COOLING ON THERMO-MECHANICAL PROPERTIES OF NON-HALOGENATED CORE

Mohan Sai Ramalingam, Supervising Professor: Dr. Dereje Agonafer, The University of Texas at Arlington

The rise in demand for modern high-power systems, which require fast processing and frequent data storage, has resulted in an exceptional and unprecedented increase in power density and heat generation within data centers. This eventually led to the need for advanced cooling techniques that can address the challenges of managing the heat produced by the data centers. As per Moore's law and Dennard's scaling, the power densities of chips and the heat flux generated by servers are continuously increasing. [1] As a result, the dissipation of heat at the chip level has also increased, posing a significant challenge for thermal management of these chips. According to a Science Magazine article, there has been a 6% rise in global energy consumption since 2010, while the computing capacity has surged by 550%.The conventional air cooled data centers consumes almost one third of the overall energy used by the facility and it has reached its limitations owing to its low cooling capacity and high power consumption Liquid cooling has many advantages over other cooling techniques because of its high heat specific capacity and high thermal conductivity of water. Due to the direct interaction of dielectric fluids with all the components in the server, single-phase liquid immersion cooling (Sp-LIC) addresses mentioned problem by offering a significantly greater thermal mass and a high percentage of heat dissipation. The conventional air-cooled data centers consume almost one third of the overall energy used by the facility and it has reached its limitations owing to its low cooling capacity and high-power consumption. Detailed study of material compatibility of the various electronics packaging materials for immersion cooling is essential to understand their failure modes and reliability. [1] When designing electronic components, material properties such as modulus and coefficient of thermal expansion are important considerations, particularly for the substrate. The substrate is a crucial element of an electronic package and significantly impacts the failure mechanism and reliability of electronics, both at the package and board level. This study mainly focuses on two challenges. The first part of this study mainly focuses on the impact

of Thermal aging on thermo mechanical properties of Non- halogenated substrate core immersed in dielectric fluids for single phase immersion cooling. The second part of this study focuses on impact of thermal aging on thermos-mechanical properties of non-halogenated substrate core in the air. The complex is calculated using the loss modulus and storage modulus of a material obtained from the Dynamic Mechanical Analyzer (DMA) for each sample. The substrate core is aged in synthetic hydrocarbon fluid (EC100), Polyalphaolefin 6 (PAO 6) and ambient air for 720 hours ~ 30 days each at two different temperatures: 85 °C and 125°C and complex modulus is characterized before and after aging and the results are compared. [1][2][3]

CHAPTER 1

1.1 INTRODUCTION

A data center is a facility where an organization's data is stored, managed, and distributed through the use of IT equipment and operations. Roughly 52% of the energy utilized by datacenters is attributed to demand-side systems within IT equipment, such as processors, server power supplies, storage, and communication, as well as other services. Meanwhile, the remaining 48% of energy consumption is attributed to supply-side systems, such as cooling, lighting, uninterruptible power supplies (UPS), switch gears, and power distribution units (PDU).[1]

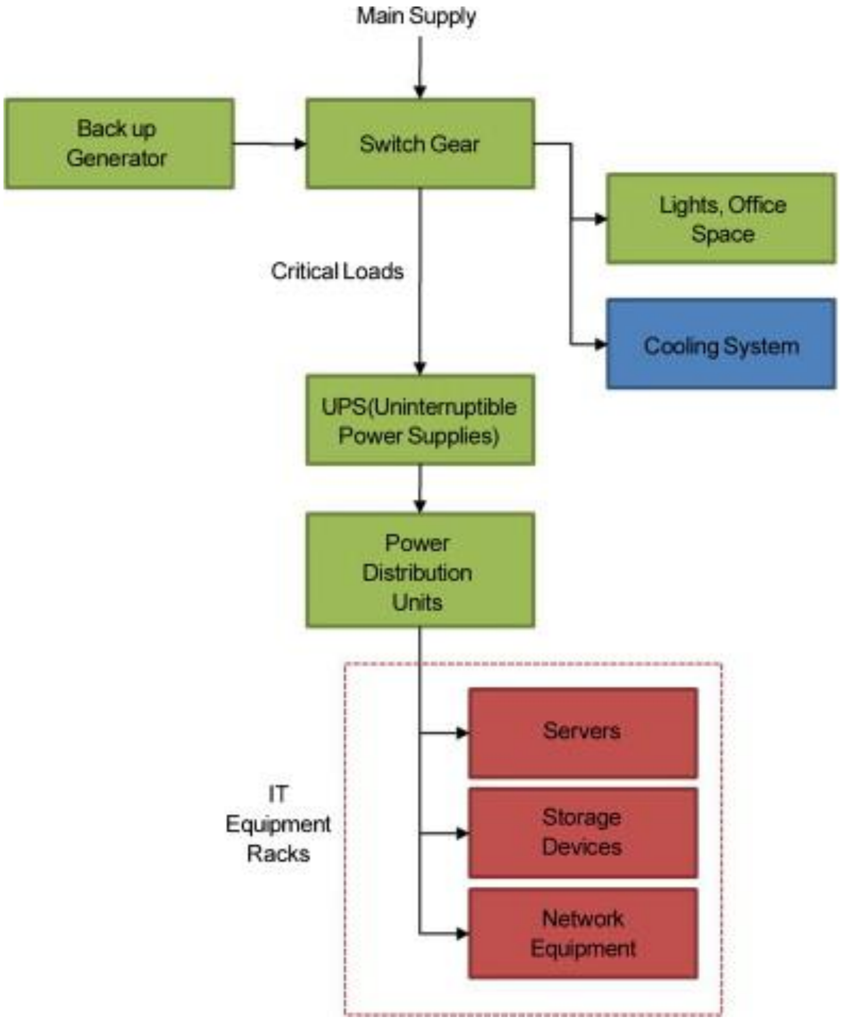


Figure 1 : Typical electrical components in a datacenter [5]

1.2 Data Center Power Consumption

The growing demand for advanced technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and Machine Learning (ML) has resulted in an increased need for extensive data storage capabilities.[1] However, this increase in data storage capacity leads to a corresponding rise in heat generation from microchips. To ensure the reliable functioning of these high-powered systems, effective cooling measures are necessary. Although there have been significant advancements in thermal management of electronic devices and microprocessors over the past few decades, there remain significant technical obstacles.[3] Two of the primary cooling challenges include effectively removing increased heat flux and managing highly non-uniform power dissipation. It was estimated that high-performance microprocessor chips would have a maximum power dissipation of approximately 360 watts and a heat flux of 190 W/ cm2The capacity of a data center is determined by its power density, which was previously measured in W/sqft but is now measured in kW/rack. In the past, a power density of 2 to 4 kW/rack was considered high, but by 2016, it had increased to 10 to 12 kW/rack. Generally, a high-density configuration is defined as exceeding 150 W/sqft. Currently, approximately two-thirds of data centers in the US are encountering peak densities of around 15 to 16 kW/rack [4].

Data center efficiency is determined in terms of Power Usage Effectiveness (PUE). That is given by [2]

$$\text{Data Center PUE} = \text{Total Data Center Power} / \text{Total IT Power}$$

Following graph shows the Cooling techniques for data center and supported power densities and PUEs

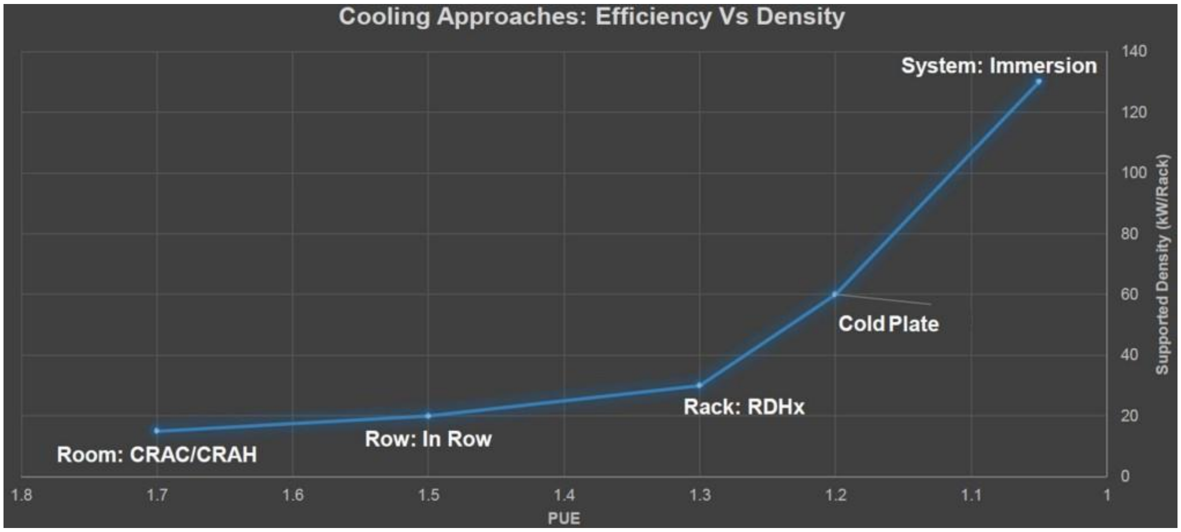


Figure 2: DIFFERENT COOLING APPROACHES ALONG WITH THEIR PUE AND SUPPORTED RACK POWER DENSITY [1]

From the graph the Power Usage Effectiveness (PUE) is higher for the immersion compared to other cooling techniques.

The Uptime Institute conducted a survey involving more than 1,100 data centers, and the results indicate that the typical power usage effectiveness (PUE) of a data center ranges between 1.8 and 1.89.[1][2][3][4]

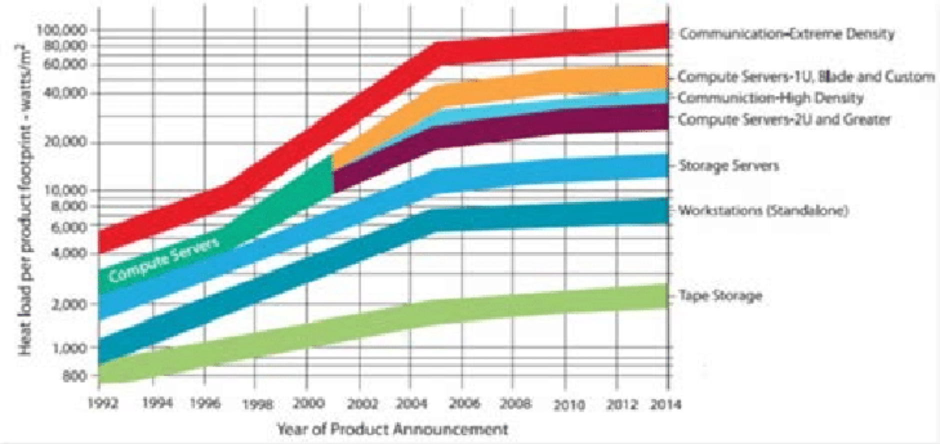


Figure 3: Power density trends for various types of information technology equipment (ITE) [23]

1.3 Cooling Technique

Various methods of data center cooling.[1][2]

1) Conventional air cooling
2) Indirect liquid cooling
3) Direct liquid cooling (Immersion cooling)

1.3.1 Conventional air cooling

Air-cooling is a method of heat removal that operates by enhancing the surface area of an object and augmenting airflow. This is achieved by attaching cooling fins to the object's surface and employing a fan to promote increased airflow.[12]The conventional method of air cooling has reached its limitations due to its limited cooling capacity, excessive energy consumption, and elevated operating expenses.[1] Due to the advancements in high-speed communication and data storage, the heat generated by modern data centers exceeds the cooling capacity of air cooling, which has a maximum power density of 30 kW per rack level. Earlier research conducted by M. Iyengar demonstrated that high-density equipment can be effectively cooled using air cooling methods. Nonetheless, employing water-cooling techniques resulted in significant operational energy savings ranging from 50.1% to 92.2%. [3]

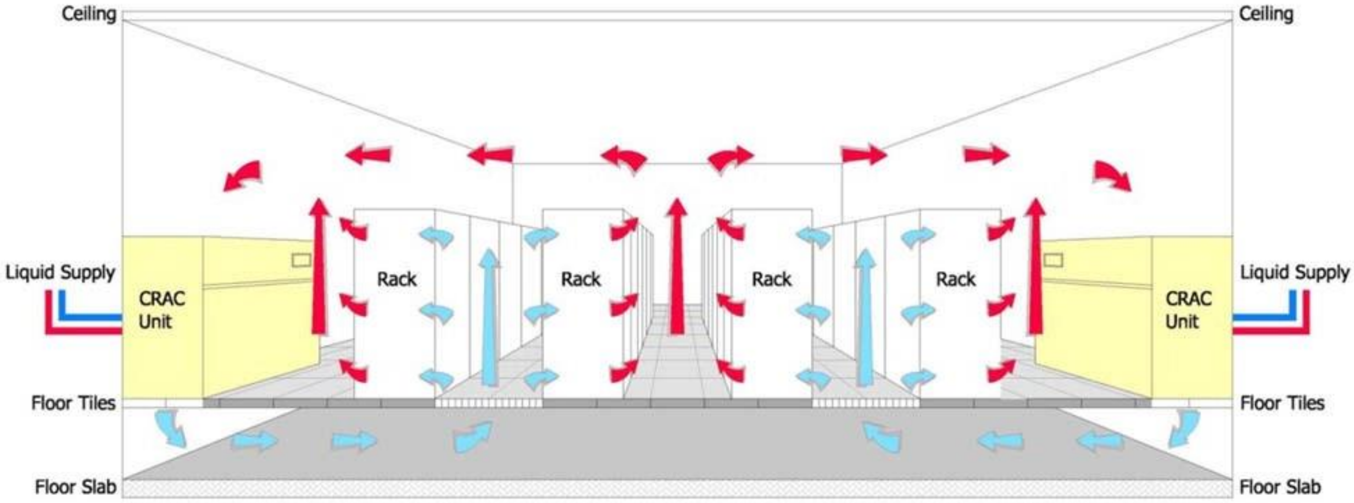
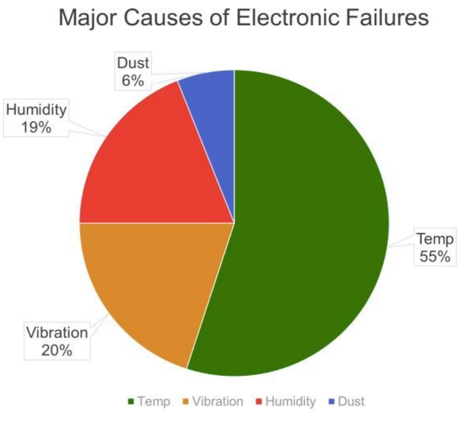


Figure 4 : Typical Raised floor data center layout [6]

According to a study by the Uptime Institute, traditional air-cooled data centers consume approximately 40% of their energy for cooling purposes, specifically for the operation of refrigeration systems such as CRAC units, HVAC fans, and HVAC cooling. However, by implementing immersion cooling, which involves submerging servers in a dielectric coolant, significant energy savings can be achieved.[1][4][2] This directly eliminates the need for HVAC cooling, HVAC fans, and CRAC units, resulting in reduced operating costs for data centers. [1-3] ASHRAE TC 9.9 indicates that typical air-cooled rack power densities range from 6 to 30 kW per rack, and for higher power densities, immersion cooling becomes a viable option. Dielectric fluids used in immersion cooling have a heat capacity approximately 1200 times greater than air, offering improved cooling efficiency and potential cost savings. Despite these advantages, the adoption of this technique remains limited due to a lack of readily available information. [3] As the thermal footprint or rack density of data centers increases, conventional air-cooling systems become inadequate for effectively provisioning and operating servers under optimal conditions. This leads to thermal throttling, where the performance of servers is limited due to excessive heat.[27] Some of the other disadvantages of Conventional air cooling is that, fans often fails and surrounding atmospheric conditions have great impact on the working and efficiency, air pollutants and condensations also have great impact on hardware damage.[4]



Source: US Air Force Avionics Integrity Program

Figure 5: Causes of Electronic Failures [4]

1.3.2 Liquid Cooled server

Liquid cooling techniques have been developed as a solution to overcome the limitations and design constraints of air-cooled servers. Air-cooled servers face inherent restrictions due to the packaging of high-powered components. In contrast, liquid has superior conductivity for both heat and electricity compared to air. This property of water, for example, is utilized to effectively cool data servers that generate substantial heat. Additionally, liquid cooling setups require less space compared to air cooling setups. The fluids used in liquid cooling can be classified into two categories. [1 – 4]

a) Water cooled serves
b) Dielectric fluid cooled servers

1.3.2.1Water cooled servers

To address the conductivity issue of water in direct contact with heat-generating components, a "Cold-Plate" system is employed in water-cooling setups. These cold plates are positioned on top of the components, such as processors, and feature a copper bottom, known for its excellent heat-conducting properties. The cold plate serves as a conduit for extracting heat from the components. A heat spreader fills the gap between the component and the cold plate, facilitating the transfer of heat from the component to the cold plate. As the heat is conducted to the cold plate, its temperature rises.[3]

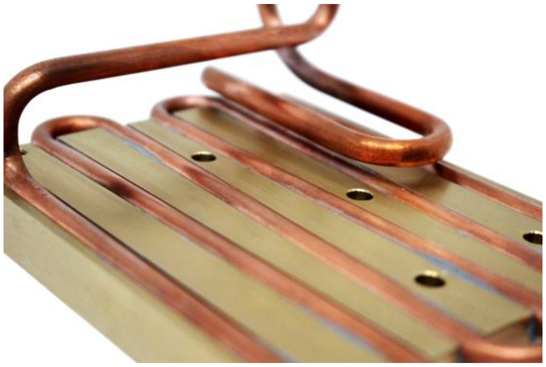


Figure 6: Cold plate [7]

1.3.2.2Dielectric fluid cooled servers

Dielectric fluids or mineral oils with high heat capacity and low electrical conductivity are used as the cooling medium. These fluids are specifically designed to be non-conductive and safe for immersing electrical components. dielectric fluids are designed to be non-conductive, ensuring the safety of the immersed components and minimizing the risk of electrical damage or short circuits. Dielectric fluids generally require less maintenance and are designed to be long-lasting. However, the initial cost of these specialized fluids can be higher. Overall, dielectric immersion cooling offers the advantage of using non-conductive fluids with high heat capacity, ensuring safe and efficient cooling. Water immersion cooling, on the other hand, leverages the excellent heat transfer properties of water but requires additional precautions to prevent electrical damage. The choice between the two cooling methods depends on factors such as specific cooling requirements, safety considerations, cost, and availability. [3]

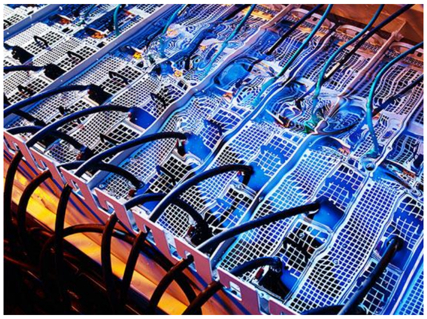


Figure 7: Dielectric Fluid immersion Cooling [8]

1.3.3 Indirect Liquid Cooling

In this cooling method, the liquid coolant is delivered directly to the hotter components, such as the CPU or GPU, by utilizing a cold plate that is placed directly on the chip. The coolant comes into contact with the cold plate, but the electric components themselves do not have direct contact with the coolant. [26] Direct-to-chip liquid cooling offers superior thermal performance compared to air cooling, it falls short in terms of effectiveness when compared to immersion cooling at high rack densities.[9] Direct-to-chip cooling commonly employs non-dielectric fluids, such as water glycol, while dielectric fluids can be utilized in direct-to-chip applications to minimize potential leaks and enhance the dependability of hardware and IT equipment.[10] Direct chip cooling has a limitation of 60 kW per rack and incurs higher operating costs when compared to immersion cooling. [1][2]

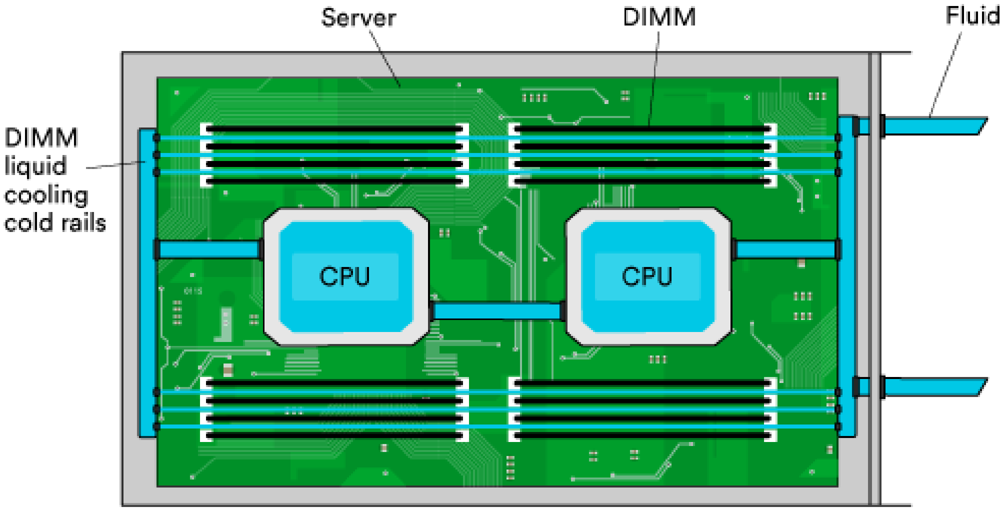


Figure 8: direct to chip cooling technique [10]

Figure 9: Cold plate used in direct to chip cooling [11]

1.3.4 Direct liquid cooling

When the temperature rises in a data center, the computing speed of its computers and servers decreases, resulting in higher energy consumption for the same workload. Traditional cooling methods in data centers are the most energy-intensive, accounting for up to 38% of the total energy usage. However, a test was conducted on a 2-kW power converter operating at 97.2% efficiency using immersion cooling in deionized water. This technology not only prevents potential damage caused by uncontrolled temperature increases but also improves energy efficiency.[12][31]

The capacity of a data center is determined by its power density, which was previously measured in W/sqft but is now measured in kW/rack. In the past, a power density of 2 to 4 kW/rack was considered high, but by 2016, it had increased to 10 to 12 kW/rack. Generally, a high-density configuration is defined as exceeding 150 W/sqft. Currently, approximately two-thirds of data centers in the US are encountering peak densities of around 15 to 16 kW/rack.[4] Liquid immersion cooling gives better cooling capacity and lower PUE than conventional cooling techniques like CRAC or CRAH. As fans, chillers or similar hardware are not required, less opex, better energy efficiency, noise reduction is achieved.[4]

Liquid cooling surpasses air cooling in effectiveness primarily due to the significant reduction in thermal resistance made possible by the use of liquid as a medium. [4]

$$QLoad = mCp\Delta T = rVCp\Delta T$$

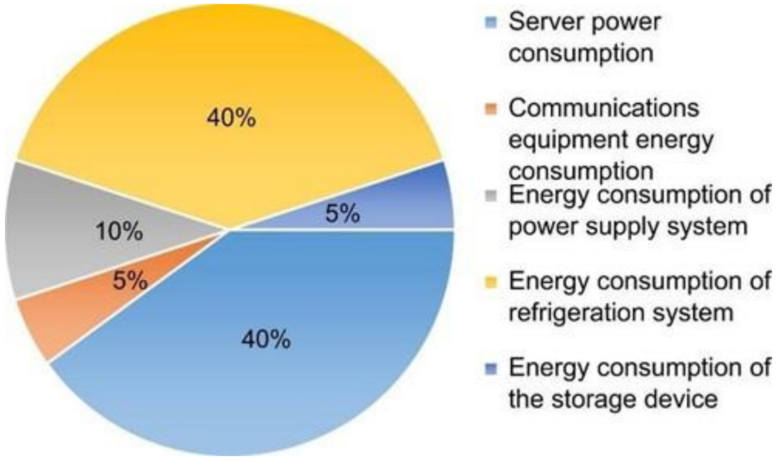


Figure 10: Typical Breakdown of Energy Consumption in Air-Cooled Data Centers [21]

Using immersion cooling as a cooling method for servers can lead to a reduction in operating costs for data centers, as approximately 40% of the energy consumed by data centers is allocated to thermal management purposes [21]

1.3.4.1 Single Phase immersion cooling

Single-phase immersion cooling maintains the coolant in a liquid state at all times, without undergoing any phase change. Open bath system is used to immerse the server filed with dielectrics as there is little or no fluid evaporation. The coolant's boiling temperature exceeds the system's maximum operating temperature.[3] The system utilizes a pump to circulate the fluid, which then absorbs heat from the coolant. Heat rejection devices such as radiators, dry coolers, liquid-to-liquid heat exchangers, or cooling towers are employed to extract heat from the system.[4]

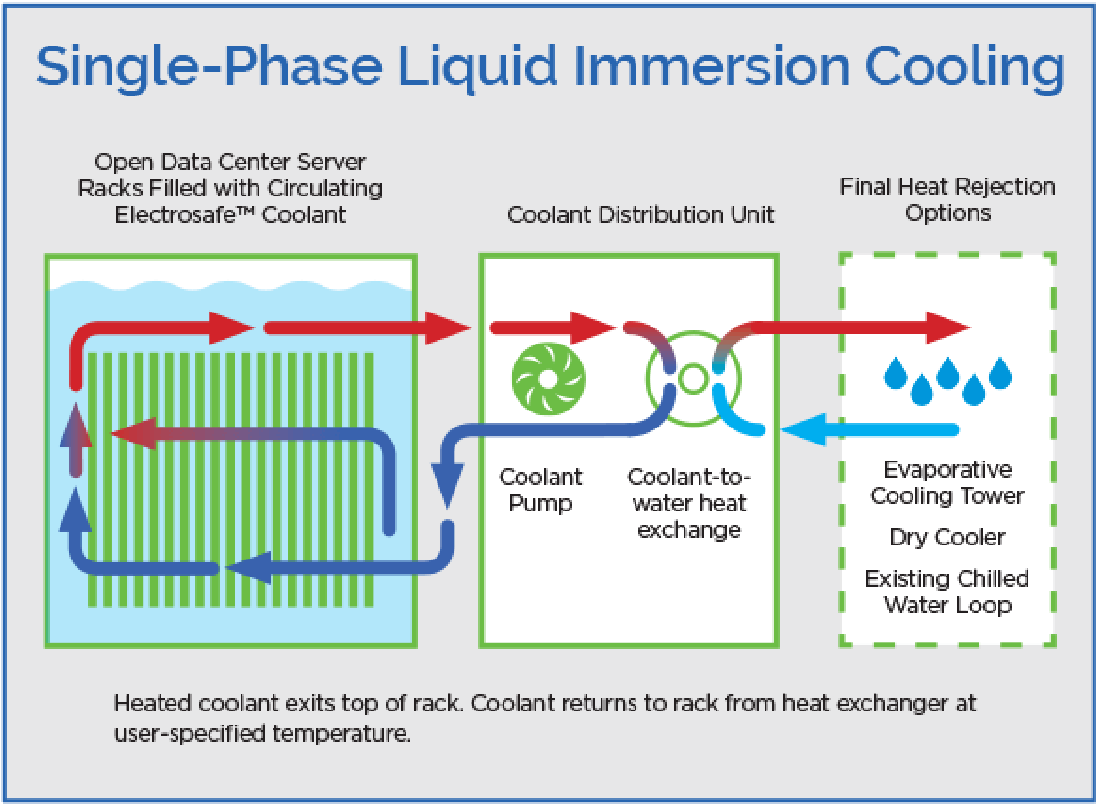


Figure 11: Schematic diagram of single-phase immersion cooling.[13]

1.3.4.2 Two Phase Immersion Cooling

Two-phase passive immersion cooling greatly enhances heat transfer efficiency by utilizing the boiling and condensation of cooling fluids. Electronic components are submerged in a non-conductive liquid bath within a sealed enclosure that allows for easy access.[14]

Heat is extracted from the chip or heat source through direct contact with the fluid, causing the fluid to reach its boiling temperature and transform into vapor. The vapor rises to the surface of the closed bath system, where it encounters a condensation coil and condenses back into a liquid state before returning to the bath. This cyclic process of evaporation and condensation is continuously repeated. The liquid coolants employed in two-phase cooling possess low boiling temperatures and exhibit low latent heat characteristics. [1 -15]

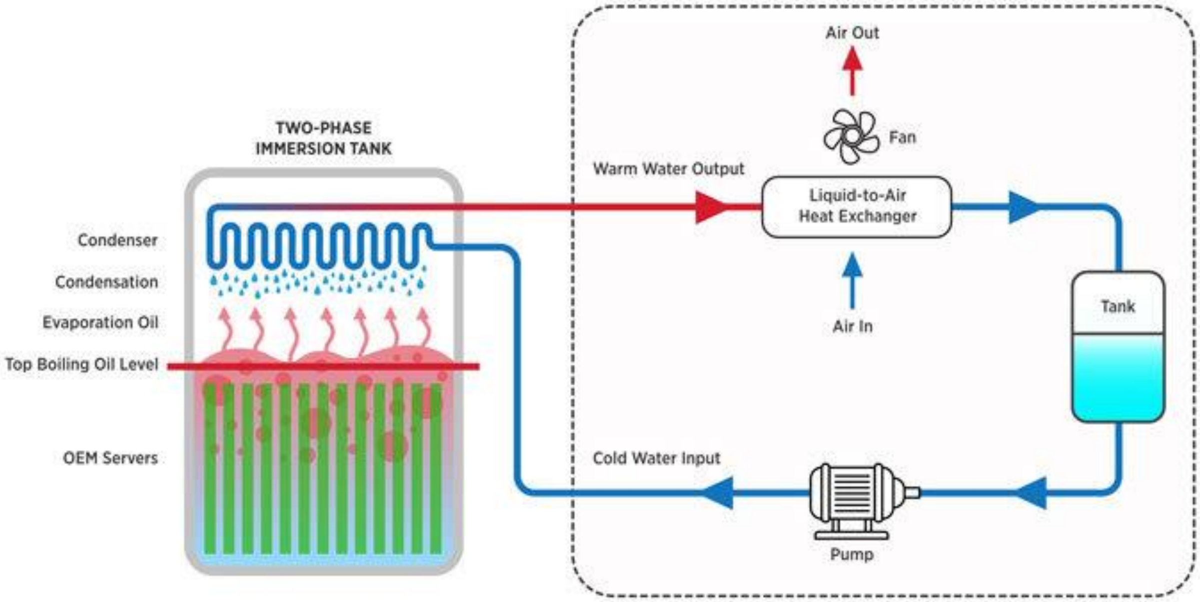


Figure 12: Schematic diagram of two-phase immersion cooling[15]

1.4 Motivation and Objective

The reliability analysis for air-cooled IT equipment has reached a mature stage. The primary causes of failures and their corresponding mechanisms have been established and defined according to the JEDEC standard for air-cooled IT equipment and electronic packaging.[2] In the electronics industry, ensuring the mechanical reliability of packages is consistently a significant concern.[1] Even a slight alteration in the material properties of the components can result in failure modes such as deformation, warpage, or delamination. These failures have the potential to compromise the integrity of the entire package. The changes in thermos- mechanical properties of the components after immersing into dielectric fluid that determines the reliability of the electronic package is unknown. Conducting a comprehensive examination of material compatibility among different electronics packaging materials in immersion cooling is crucial to gain insights into their failure modes and reliability.[1-5,][28] A detailed study is necessary to better understand how these materials interact and the potential risks or issues that may arise, thereby ensuring the reliability of the cooling system. Hence, even slight variations in how materials are prepared or tested can significantly affect the accuracy of computational models used to design or analyze sensor performance. This challenge becomes even more complex when dealing with materials that need to undergo a curing process. [24] Evaluating and selecting Substrate core for performance using finite element method (FEM) simulations can be expedited and cost-effective by considering crucial mechanical properties like modulus and coefficient of thermal expansion (CTE).[29] These properties play a significant role in assessing the performance of TIMs and can aid in streamlining the evaluation and selection process[25]

Some of the common mechanical failure modes for electronic packages are.[1]

a. Instantaneous fracture
b. Fatigue failure
c. Creep failure
d. Delamination

This study mainly focuses on the reliability of the substrate core used for immersion cooling, and the thermo-mechanical properties of the substrate subjected to different aging temperature is calculated. Substrates serve as the fundamental components that establish the connection between the package and the board in electronic systems. Interconnects are utilized to establish connections between the die and the substrate, as well as between the substrate and the board. Consequently, any deformation or warpage occurring on the substrate can disrupt the contact with the interconnects, ultimately resulting in package failure. [1-5] Therefore, it is important to guarantee the dependability of a product in order to implement appropriate strategies that reduce or delay the occurrence of product failures during the wear-out phase. [22]

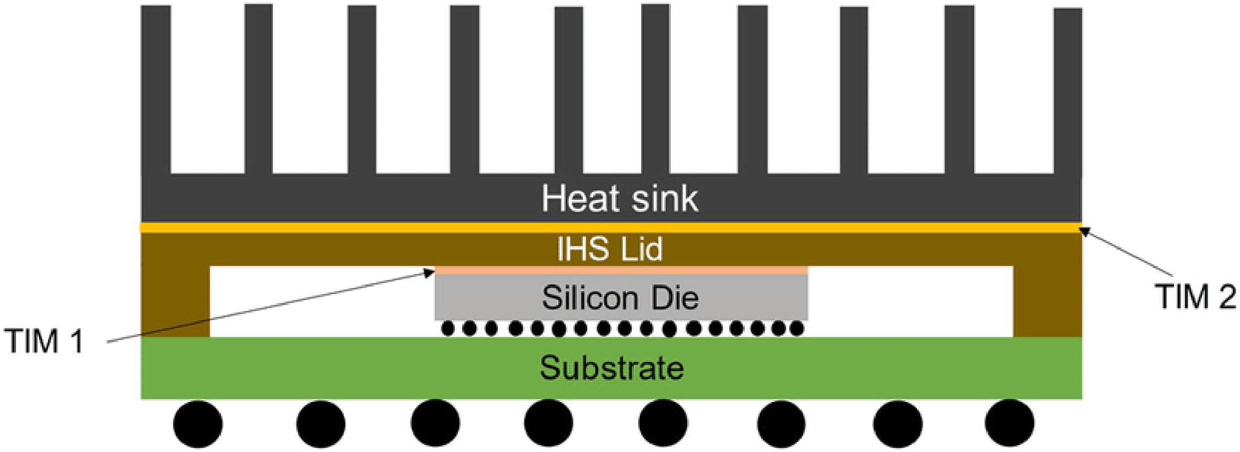


Figure 13: Schematic substrate in electronic package[16]

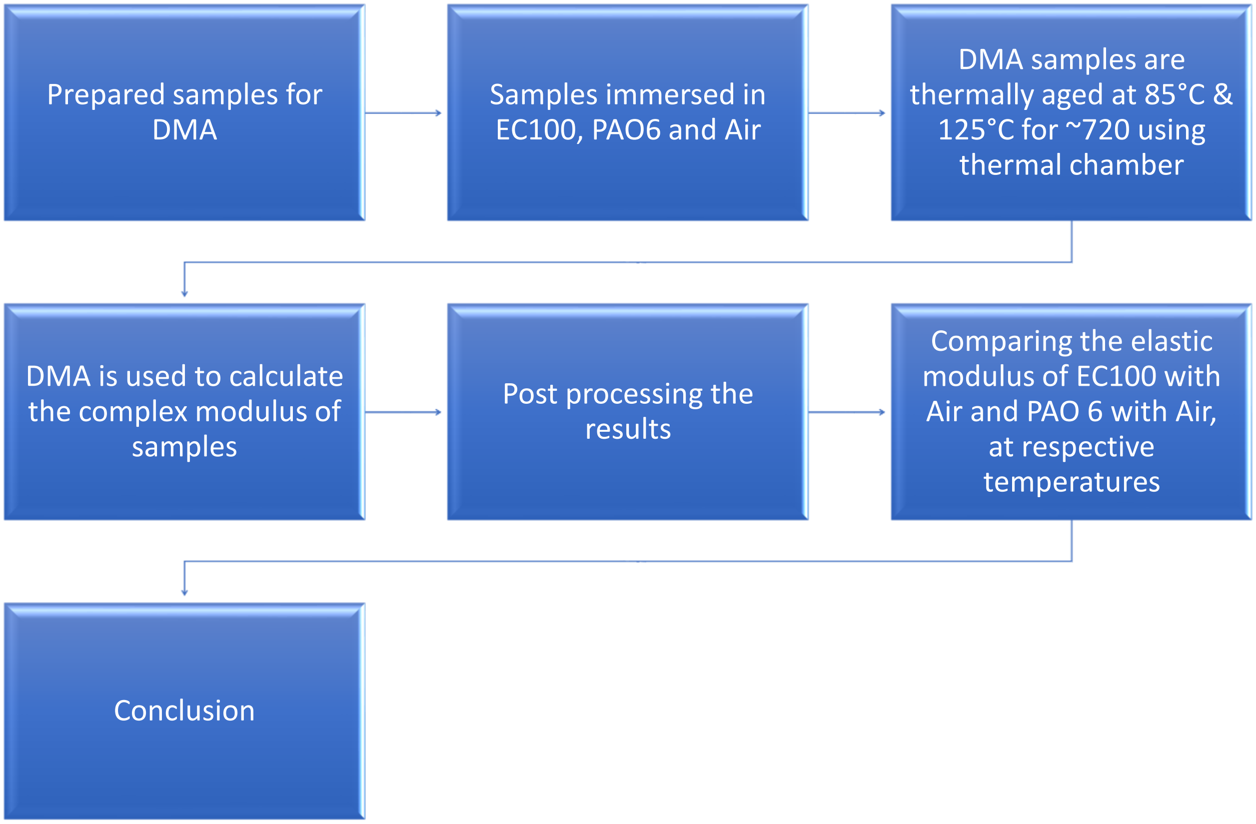
The young's modulus and Coefficient of thermal expansion is basic intrinsic material property that is used to determine the reliability of a substrate core and it can be calculated using Dynamic Mechanical analyzer (DMA) and Thermo- Mechanical Analyzer (TMA).[1-5] To calculate the mechanical properties like storage modulus, loss modulus, glass transition temperature Dynamic Mechanical Analyzer (DMA) and to calculate the thermal properties like CTE Thermo-Mechanical Analyzer (TMA) are extensively used. In this work, we have investigated the thermo-mechanical properties of non–halogenated substrate core immersed in dielectrics such as EC-100, Pao6 and Air at two different thermal aging temperatures 85°C and 125°C. Tushar et al. conducted a study on the thermo-mechanical characteristics of low loss printed circuit boards submerged in mineral oil for a duration of 720 hours at temperatures of 25, 50, 75, and 105°C. It was found that the in-plane CTE, modulus of post-aged samples did not vary significantly at these temperatures as the glass transition temperature is very high. [1-5] Rabin et. Al worked on a similar study with non-halogenated substrate core submerged in EC-100 and Air at 22,50, and 75°C for 720 hours and the complex modulus is characterized before and after aging and compared. it was found that modulus of samples immersed in EC-100 was higher when compared with the samples exposed to air at 75°C.[1-2]

This work mainly deals with the single-phase immersion dielectric fluids EC 100 and Pao6 on the mechanical property of non-halogenated substrate after immersing the samples for 720 hours at 85°C and 125°C. Thermal chamber is used to maintain the thermal aging temperature of 85°C and 125°C. Liquid nitrogen is used to achieve temperature of -35°C.

Dynamic Mechanical Analyzer (DMA) is used to measure the Storage modulus (E') and loss modulus (E") for each sample subjected to different dielectric and thermal aging temperatures.[1][2]

Youngs modulus (E*) is calculated using the data obtained from the Dynamic Mechanical Analyzer and compared to determine the thermo- mechanical property.[1]

1.6 OUTLINE


Prepared samples for DMA
Samples immersed in EC100, PAO6 and Air
DMA samples are thermally aged at 85°C & 125°C for ~720 using thermal chamber
DMA is used to calculate the complex modulus of samples
Post processing the results
Comparing the elastic modulus of EC100 with Air and PAO 6 with Air, at respective temperatures
Conclusion

CHAPTER 2

2.1 Materials and methods

2.1.1 Dynamic Mechanical Analyzer (DMA)

Dynamic Mechanical analyzer is the technique used to measure sample's kinetic properties elasticity and viscosity. samples response is monitored under applied sinusoidal stress/ strain and plotted against temperature, time, or frequency. In this study DMA 7100 used to calculate the complex modulus of the substrate. DMA consist of a probe, displacement detector, force generator, thermocouple and furnace. [1-5]

The Complex Modulus, whose magnitude is comparable to young's modulus can be obtained using equation (1) using storage and loss modulus. [2]

$$E^* = E' + iE'' \qquad (1)$$

$$E^* = \sqrt{(E')^2 + (E'')^2} \qquad (2)$$

$$Tan\ \delta = \frac{E''}{E'} \qquad (3)$$

Where,

E*= Elastic Modulus

E'= Storage modulus

E' = Loss modulus

The DMA used in this experiment can be used to reach temperature range of -150°C and 600°C with heating rate ranging from 0.01 to 20°C/min and the frequency ranges from 0.01 to 200 HZ. With the LN2 Cooling Unit option, a sample can be cooled down to -150°C. [17]

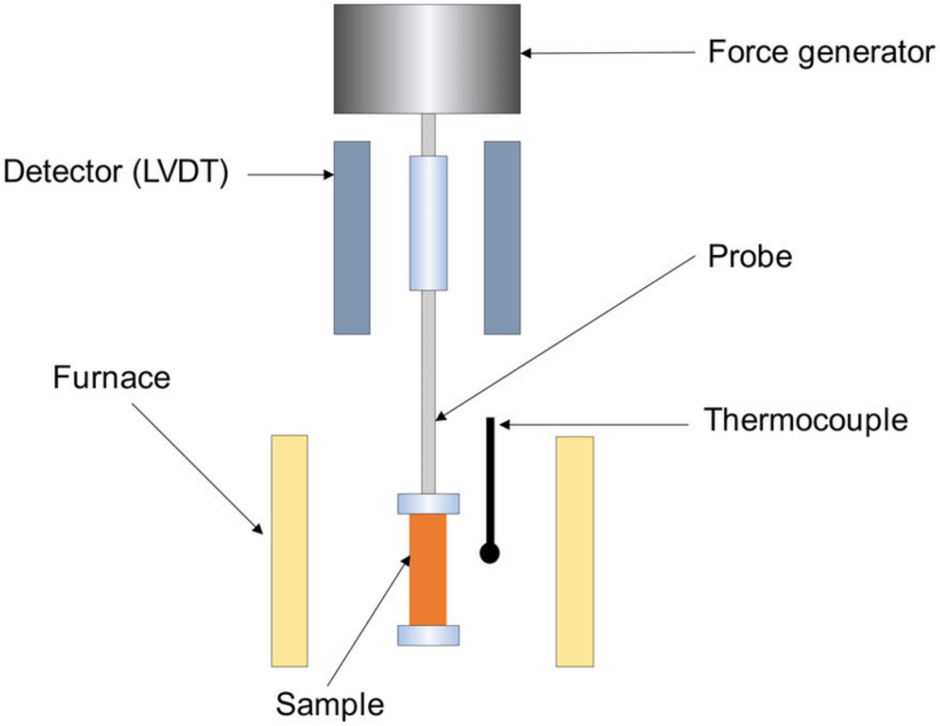


Fig 14: Dynamic Mechanical Analyzer (DMA)[17]

2.1.2 Tension Attachment

Dynamic mechanical Analyzer has different attachments that is connected to the probe through which the samples sinusoidal stress is measured in accordance with the applied sinusoidal stress at various frequencies and temperature. Tension attachment is generally used for the which are harder or say thickness of the material is less. This following picture shows the tensile attachment with sample attached vertically. while testing the sample the effective length of the samples remains 20mm.[1 – 5]

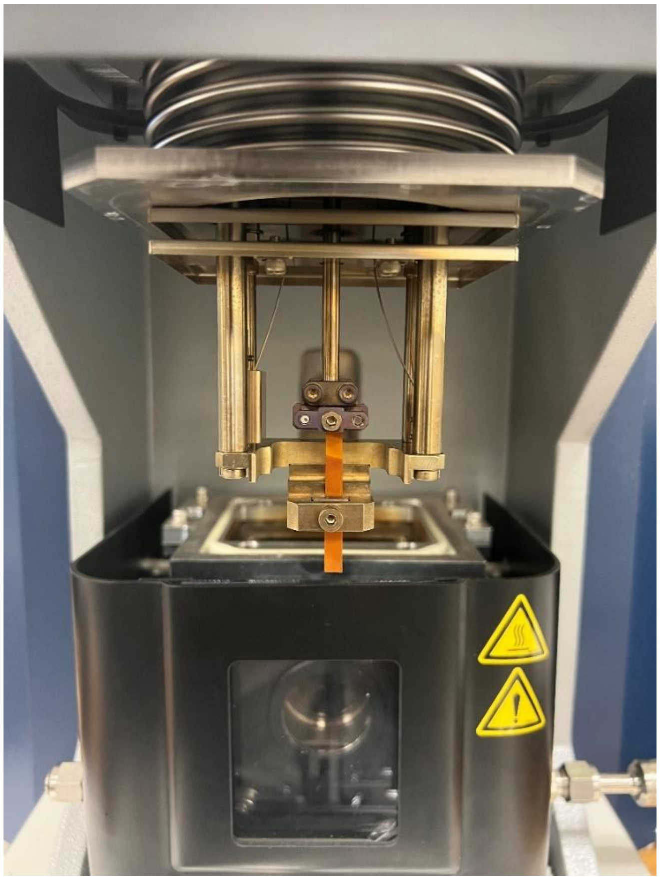


Figure15: Tension attachment with sample IS550H

The following Table shows the DMA 7100 Technical specifications

Table1: DMA 7100 Technical specifications [19]

Deformation mode	Tension, bending, shear, film shear, compression, 3-point bending
Frequency	Sine wave oscillation….0.01 to 200Hz
Measurement Range	105 to 1012Pa(Tension), 105 to 1012Pa(Dual-Cantilever Bending), 103 to 109Pa(Shear), 104 to 1010Pa(Film Shear), 105 to 109Pa(Compression), 106.5 to 1013.5Pa(3-Point Bending)
Program temp range	-150°C to 600°C
Heating range	0.01 to 20°C/min
Output values	Temperature, Frequency, Time, E’(G’), E” (G”),| E*|(|G*|), tanδ, η, J’, J”, Ft, dL, Stress, Strain

2.1.3 Thermal Chamber

To study the impact of thermal aging on the non-halogenated substrate core immersed in Dielectrics fluids EC100, Pao6 and exposed to Air, thermal chamber is used. It helps in maintaining the temperatures requirements for this study. The samples used for the study are thermally aged at 85°C and 125°C for ~720 hours.[1]

Figure16: Thermal chamber with furnace containing thermal aging samples

CHAPTER 3

3.1Sample Preparation

3.1.1 Cutting samples for required dimensions

The samples used for this study is IS550H. It is mainly used In High Voltage and power applications which require extremely high thermal stability. The ~0.2mm thick IS550H samples is cut into four samples for each case of thermal aging dielectric samples to ensure the statistical accuracy. The overall dimensions of the samples used for this study are length 50mm and width 4mm approximately. Total of 24 samples are prepared with the dimensions in accordance with Dynamic Mechanical Analyzer (DMA) standards. [1]

(A) (B)

Figure 17: Dimensions of DMA Samples (A) Length of ISS550H (50mm), (B) width of IS550H (5mm)

3.2 Thermal Aging

Aging experiments were conducted under 6 distinct conditions, each characterized by specific environmental parameters namely, the temperature and type of fluid used for aging. The DMA samples are placed in dielectric fluids EC100, Pao6 and exposed to air at 85°C and 125°C for ~720 hours (30 days). Following table shows the aging of IS550H samples in air and dielectric fluids .

Table 2. Aging of the IS550H samples in air and dielectric fluid and thermal aging temperature

Aging time	**Aging temperature**	**No of samples immersed in Ec100**	**No of samples immersed in Pao6**	**No of samples in air**
~720 hrs	**85°C**	4 DMA samples	4 DMA samples	4 DMA samples
	125°C	4 DMA samples	4 DMA samples	4 DMA samples

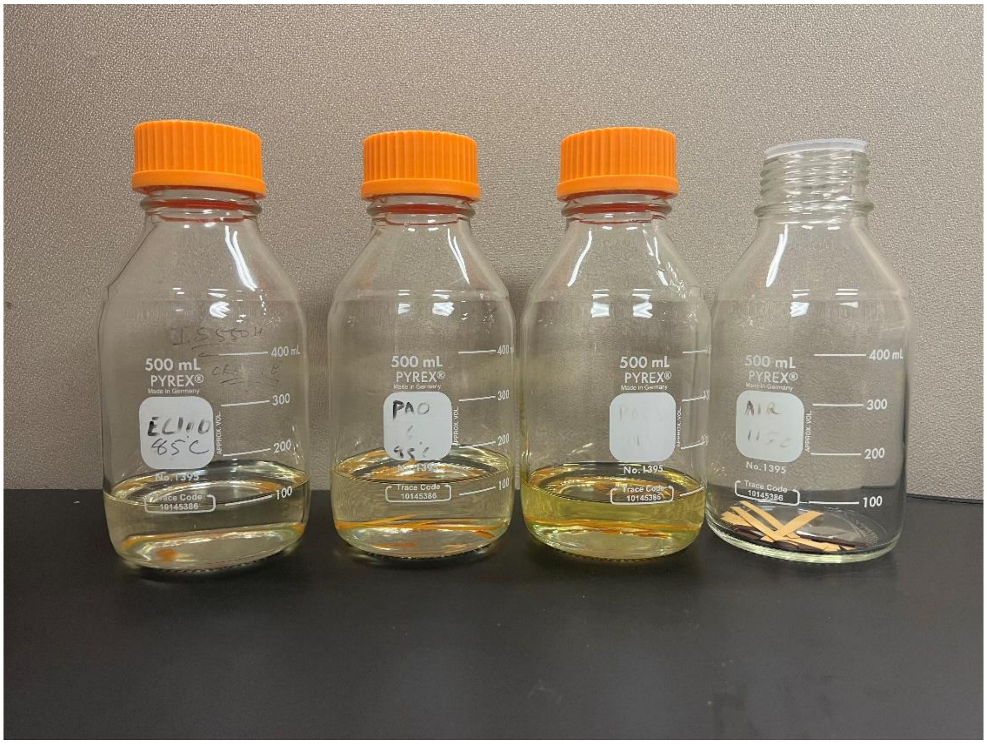


Figure 18. Furnace containing IS550H aging samples immersed in Dielectrics and air

Table 3: Material properties of IS550H sample [20]

Property		**Typical Value**	**Units**	**Test Method**
			Metric (English)	**IPC-TM-650 (or as noted)**
Glass Transition Temperature (Tg) by DSC		200	°C	**2.4.25C**
Decomposition Temperature (Td) by TGA @ 5% weight loss		400	°C	**2.4.24.6**
Time to Delaminate by TMA (Copper removed)	A. T260 B. T288	>60	Minutes	**2.4.24.1**
Z-Axis CTE	A. Pre-Tg	38	ppm/°C ppm/°C	**2.4.24C**
	B. Post-Tg	210	%	
	C. 50 to 260°C, (Total Expansion)	2.2		
X/Y-Axis CTE	Pre-Tg	13-17	ppm/°C	**2.4.24C**
Thermal Conductivity		**0.7**	**W/m·K**	**ASTM E1952**

Chapter 4

4.1 Experimental procedure

DMA samples used for this study has a dimension of ~50 mm, width of 4 mm and 0.2 mm thickness. Digital calipers with 0.02mm accuracy is used to measure the samples dimensions. Based on the predicted modulus of the material and the sample geometry factor calculated from sample dimension, tension attachment is used to measure the storage and loss modulus of the samples. The Samples used Total of 24 samples are prepared with the dimensions in accordance with Dynamic Mechanical Analyzer (DMA) standards. The samples are subjected to sinusoidal stress/strain through a tension attachment and the measurement of loss modulus and storage modulus is measured against temperature and frequency. The experiment was performed for for the following frequencies 0.5, 1 , 2 , 5 and 10 Hz frequencies and temperature range from -35°C to 200 °C , liquid nitrogen is used to achieve the temperature of -35℃. Industry commonly selects frequencies based on the consideration of material behavior, which can vary with frequency and temperature. Frequency 1 Hz is used to calculate the complex modulus of the sample. To stabilize temperature fluctuations within a range of +/- 3°C, an isothermal hold was conducted initially at -35°C. In order to minimize the lag between the sample temperature and furnace temperature caused by the thermal mass of the sample, a slower heating rate of 4°C per minute was employed during the experiment, as opposed to the faster rate of 10°C per minute. [2]

Following table contains the DMA settings used for the tensile mode.

Table 4: DMA settings used for this experiment [2]

Parameters	Value
Minimum tension/ compression force	200 mN
Tension/ compression force gain	1.5
Force amplitude	2000 mN
L Amplitude	10 um

The maximum time required to measure the samples within specified temperature is about ~1 hr. and the time to reach isothermal temperature of -35°C is ~1 hr. Following graph shows the maximum time to reach the temperature (200°c) with the ramp rate of 4°c/ min.

Figure 19: Graph representing the total time required to test the sample

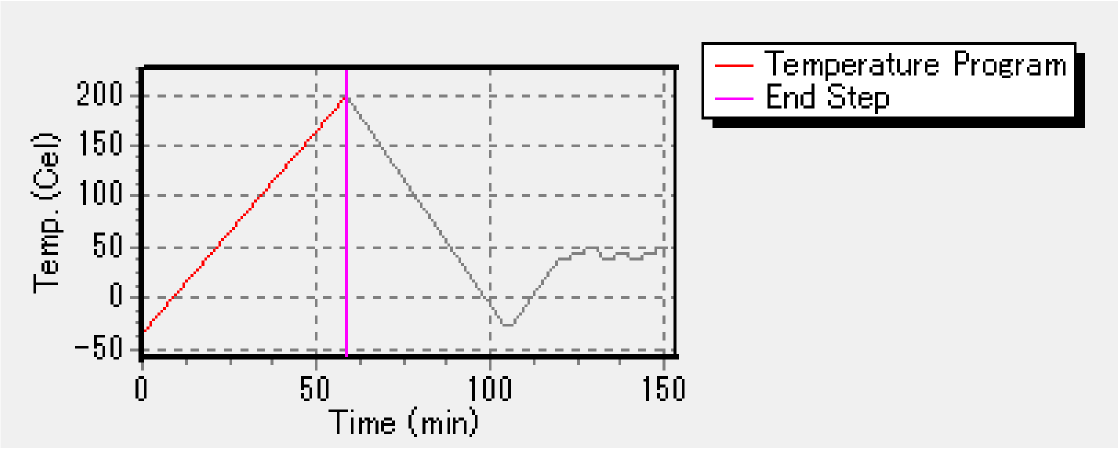


Figure 20: Dynamic Mechanical Analyzer (DMA) [19]

4.2 DMA Test output

The following figure shows the DMA output of samples exposed to air at 85°C, the green line represents the storage modulus (E'), red represents the loss modulus (E") and blue represents the damping ratio of the sample for the frequencies of 0.5,1,2,5 and 10 Hz.

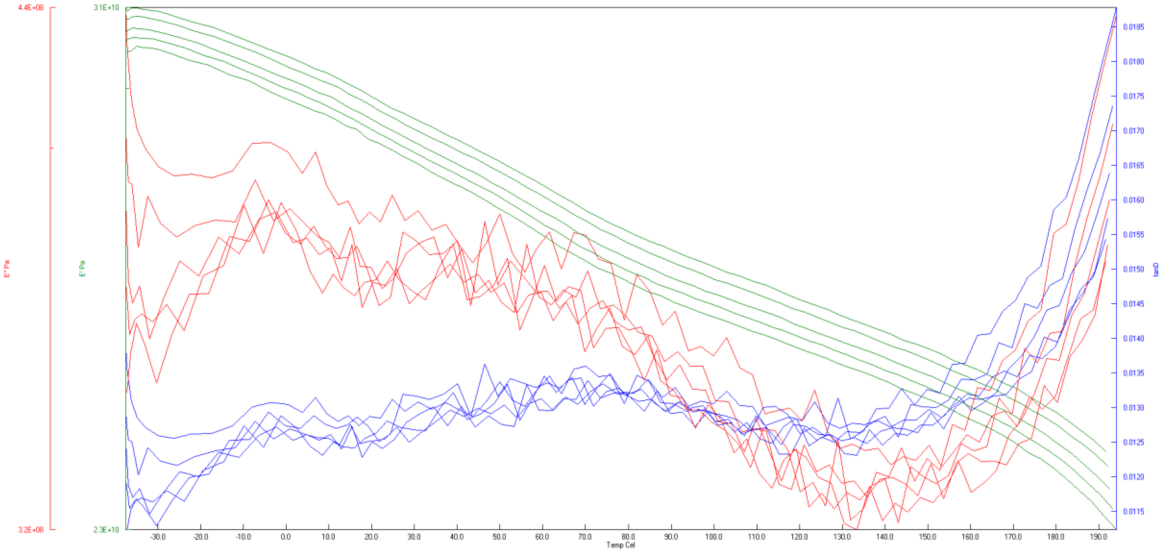


Figure 21: DMA results of sample immersed in Air at 85°C

CHAPTER 5

5.1 RESULTS

5.1.2 DMA results

Complex modulus of each sample for different temperatures

Figure to figure, shows the graph comparing the elastic modulus (E*) for the immersed and non-immersed sample at 85° C and 125°C respectively. Each aging fluid has 4 samples immersed for both the aging temperature. 4 samples for each case are measured for loss modulus and storage modulus, complex modulus for each sample is measured. [1]The standard deviation at different intervals for each sample is applied across the temperature(°C). the average of the complex modulus with the standard deviation of samples immersed in EC100, Pao6 and Air for the temperature ranging from -35°C to 125°C is compared In the figure below. From the postprocessing of the DMA output we can compare the samples elastic modulus and find the reliability of the substrate core as it is the important component in the electronic packaging. We can conclude the most reliable samples based on the value of complex modulus, the lower the elastic modulus of the substrate the higher reliability of the substrate. [1-10]

Figure 20 shows the combined plot for all samples immersed in EC100, Pao6 and Air thermally aged at 125°C along with the standard deviation of the samples. [1]

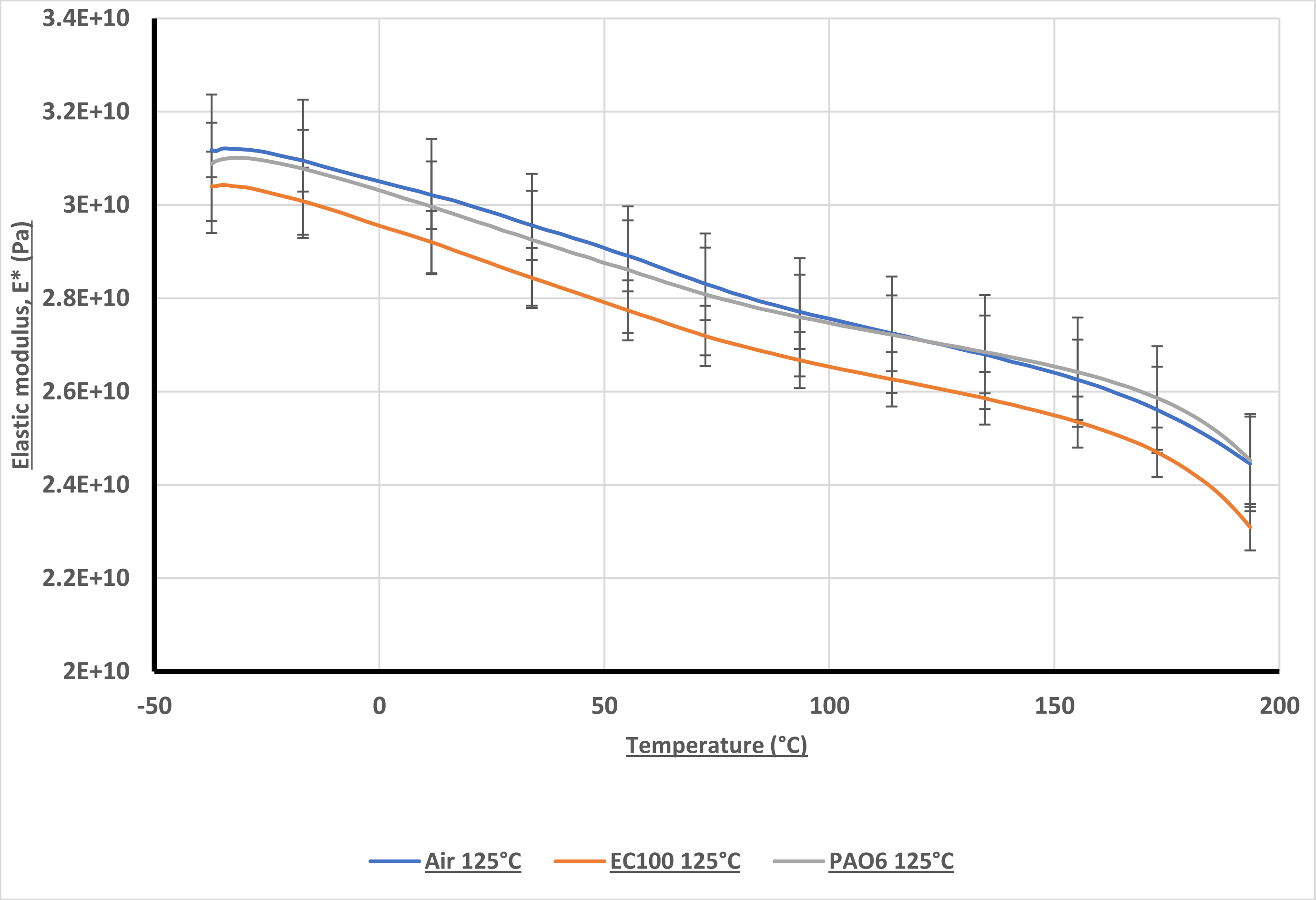


Figure 22: comparison of elastic modulus of sample immersed in ec100, pao6 and air at 125°c

Figure 20 shows the combined plot for all samples immersed in EC100, Pao6 and Air thermally aged at 85°C along with the standard deviation of the samples. [1]

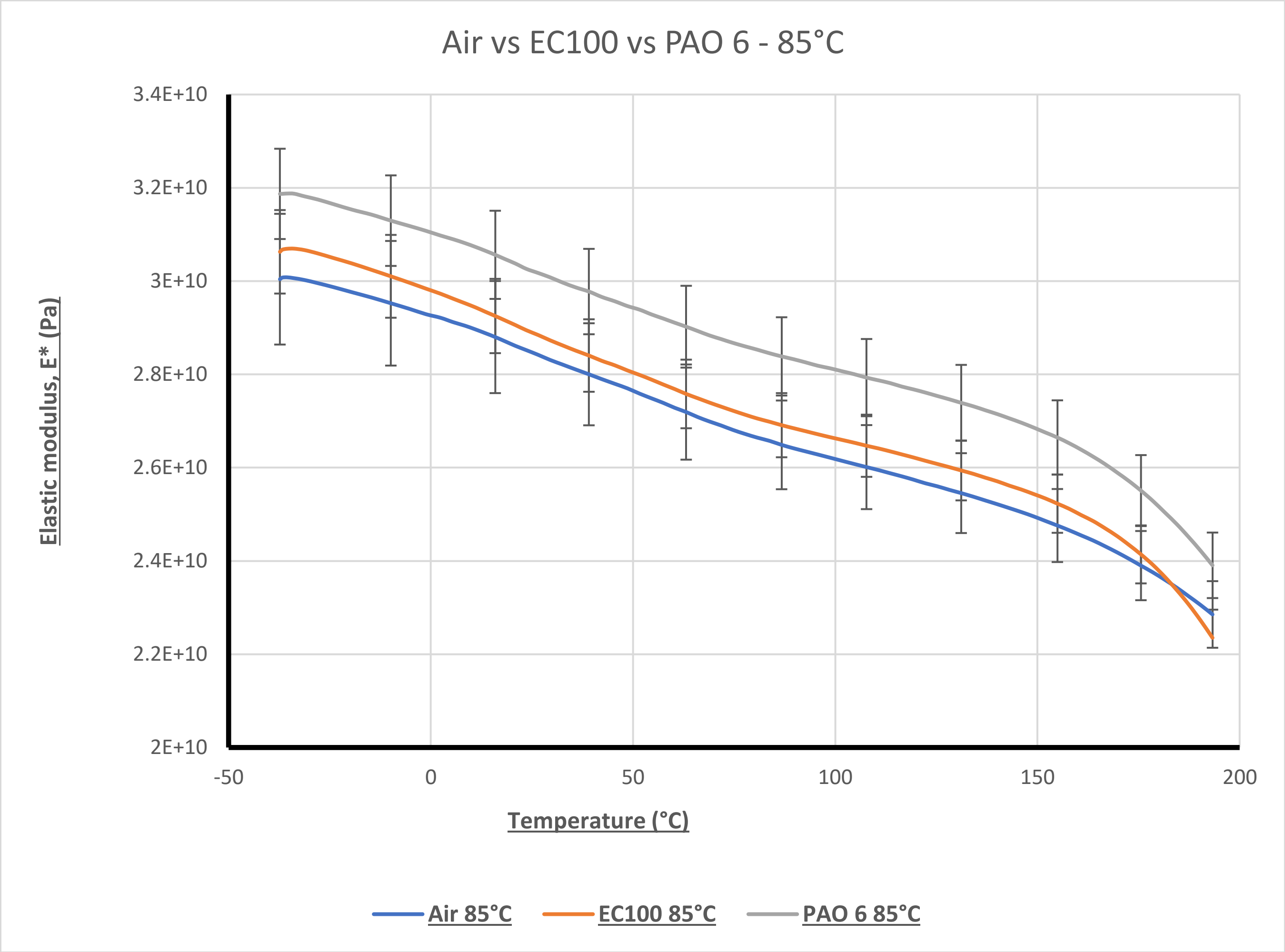


Figure 23: comparison of elastic modulus of samples in ec100, pao6 and air 85°c

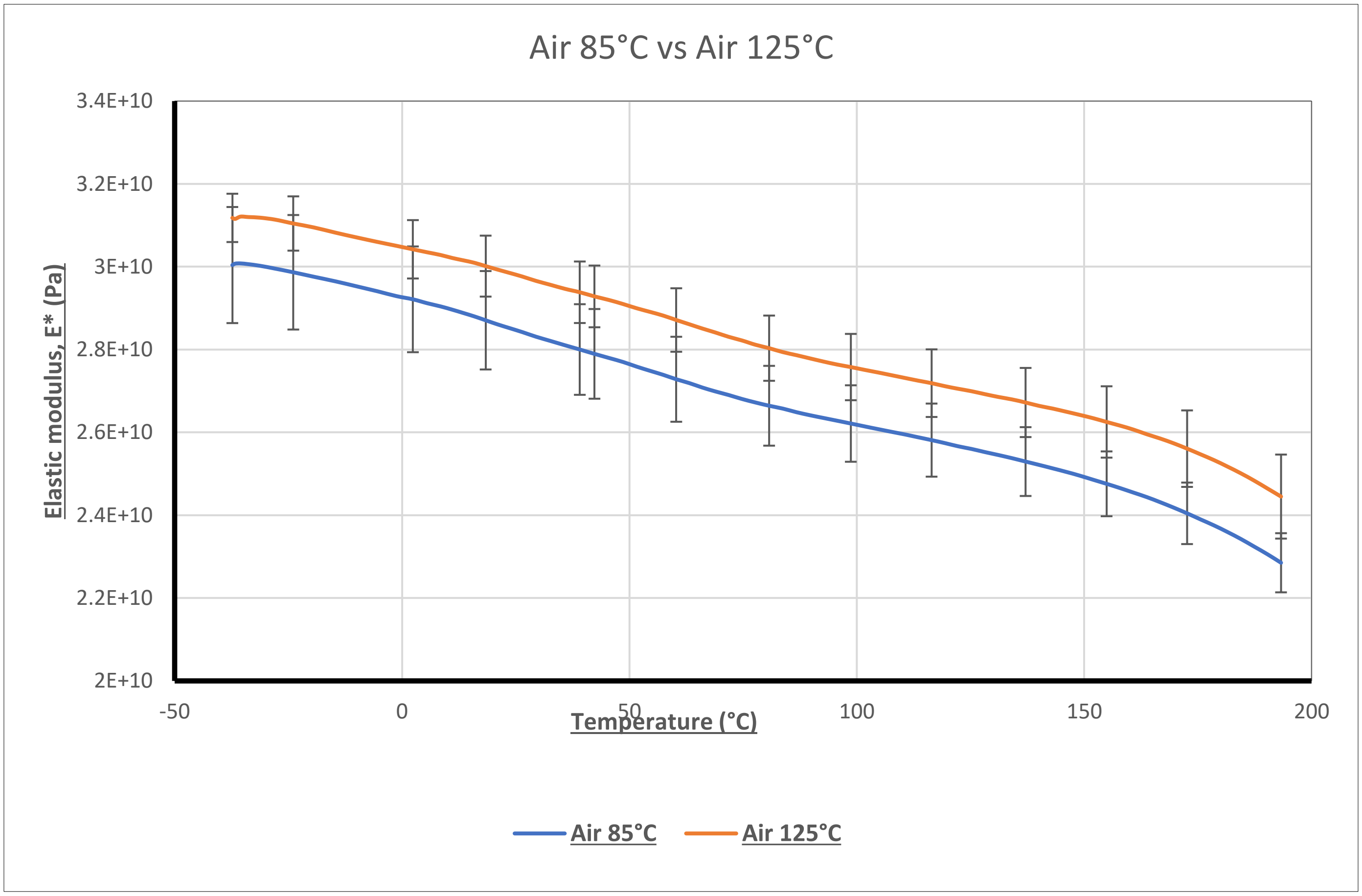


Figure 24: comparison of elastic modulus of samples exposed to air at 85°c and 125°c

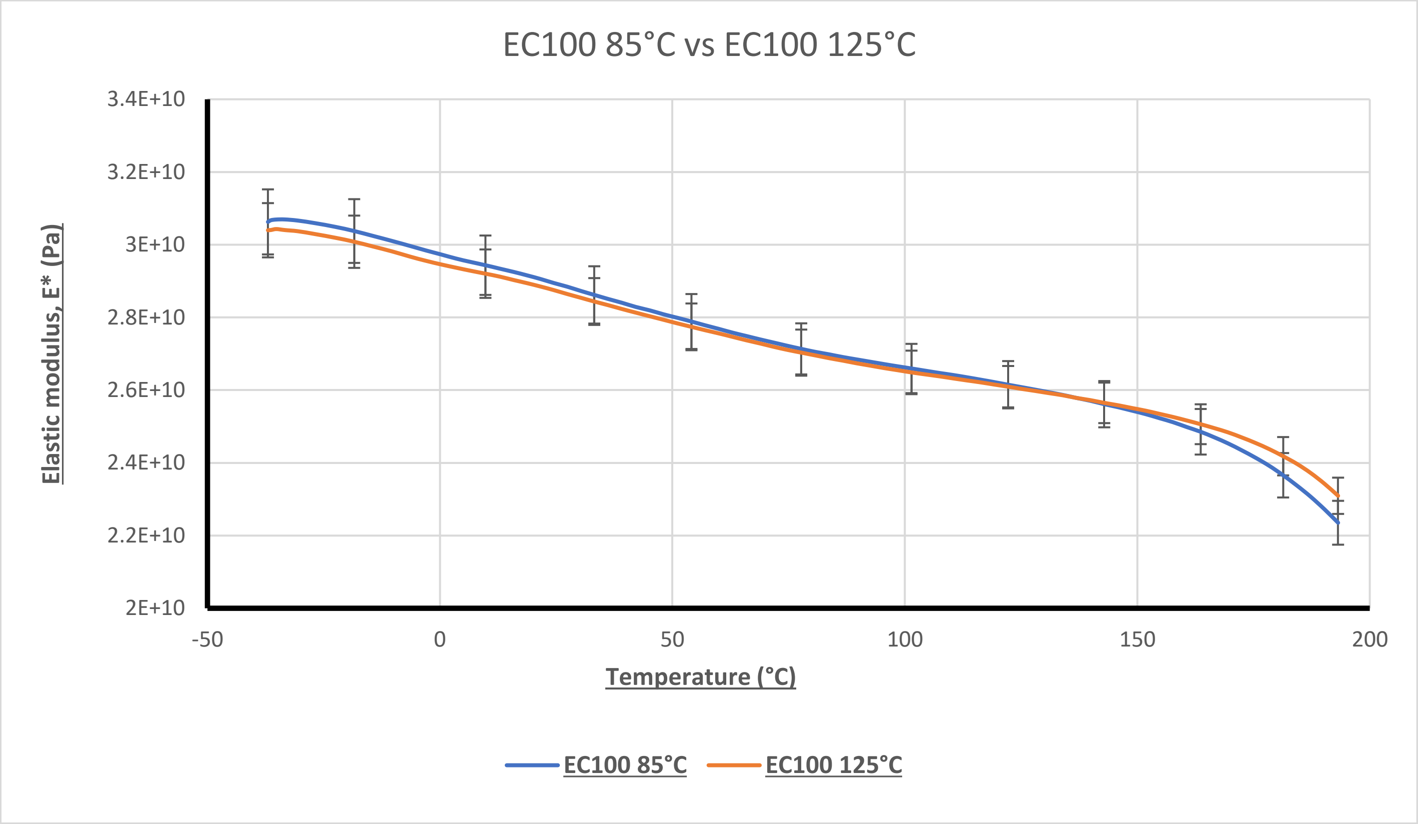


Figure 25: comparison of elastic modulus of samples immersed in ec100 at 85°c and 125°c

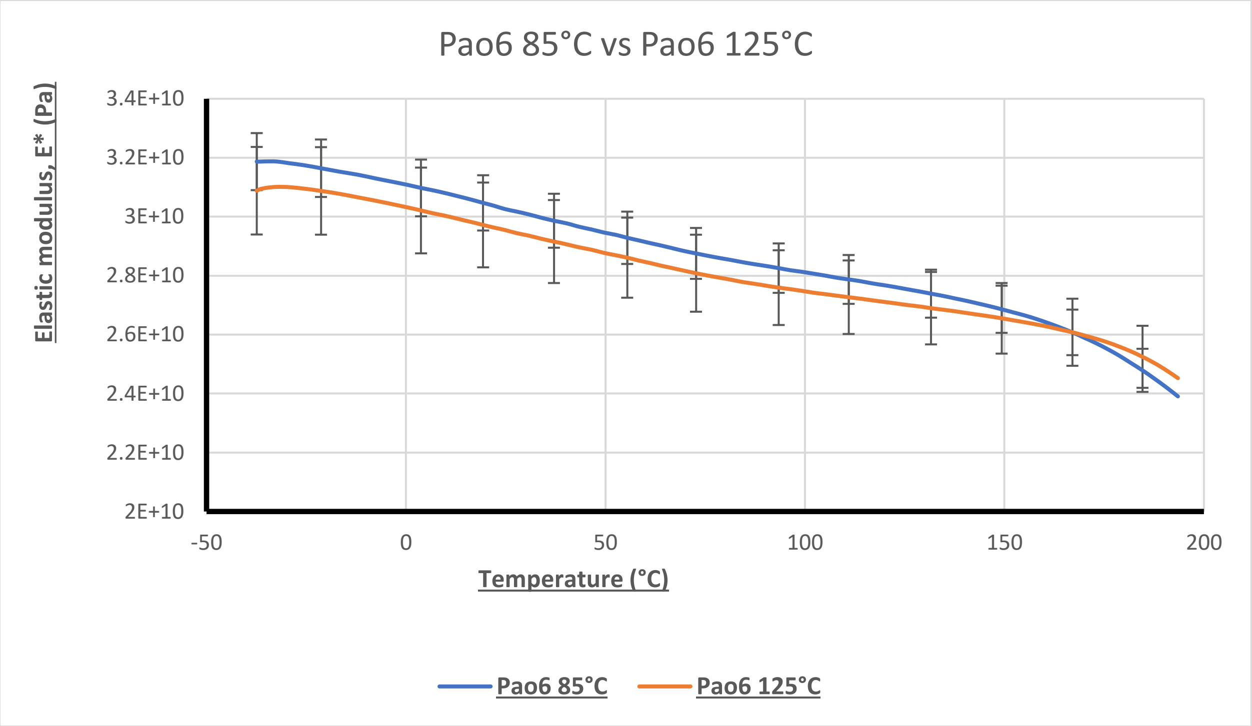


Figure 26: comparison of elastic modulus of sample immersed in poa6 85°c and 125°c

CHAPTER 6

6.1Result Discussion

In section of results, Figure to figure, the comparison of results for DMA Measurements for IS550H samples aged in Dielectric liquid and aged in air at two different temperatures 85°C and 125°C, for plotting each graph for samples aged in different temperature and fluid, 4 samples were tested and averaged. The complex modulus is plotted against temperature. Standard deviation for each is calculated plotted against temperature. Standard deviation for each sample is calculated to difference values of complex modulus (E*) due to the variation in copper connections, slight variation in samples width and density, that causes large variation in error bars. Predefined torque was applied to minimize the variation in clamping force to attach sample (tushar), Isothermal hold was performed to measure the thermo-mechanical properties of the samples at -35°C and maximum temperature used for testing the samples in DMA is 200°C. The main reason to choose this temperature range is because most of the IT equipment's operated in temperature range of -40°C to 85°c, for the most extreme condition local temperature on the substrate can reach more than 125°C. when we characterize materials, ideally, we want to capture the whole profile hence -35°C. The reason behind the maximum temperature used in this experiment is glass transition temperature (Tg), the presented data shows the glass transition temperature of IS550H substrate core is 200°C. The maximum duration of the test is ~1hr since the isothermal hold is performed in the beginning the total time required to test the sample is ~2 hr. Figure 1 displays a combined plot illustrating the standard deviation of the complex modulus at 125°C for samples immersed in EC100, PAO 6, and Air. The average complex modulus (E*) indicates that the samples exposed to air have the highest modulus, while the samples immersed in EC100 have the lowest. The reliability of a material is typically determined by its elastic modulus, where lower values of E* indicate higher substrate reliability. Based on this criterion, the samples immersed in EC100 at 85°C exhibit greater reliability compared to those immersed in PAO 6 and Air at the same temperature. Figure 2 presents a combined plot showcasing the standard deviation of the complex modulus at 85°C for samples immersed in EC100, PAO 6, and Air. By comparing the modulus values, it is observed that the samples exposed to PAO 6 have the highest modulus, while those immersed in EC100 have the lowest. Interestingly, in this case, the samples exposed to air at 85°C demonstrate greater reliability compared to the other aging environments. It is worth noting the varying trend of the samples aged at 85°C compared to those aged at 125°C. Figures 3 to 5 provide a comparison of modulus values for samples aged at two different thermal temperatures: PAO 6 at 85°C versus PAO 6 at 125°C, EC100 at 85°C versus EC100 at 125°C, and Air at 85°C versus Air at 125°C.[1][2]

CHAPTER 7

7.1 Conclusion and future work

In summary, the Impact of thermal aging of non-Halogenated substrate core immersed in dielectric fluids Such as EC100, PAO 6 and Air using Dynamic Mechanical analyzer. A total of 24 substrate samples were subjected to thermal aging in EC100, PAO6, and Air at both 85°C and 125°C for approximately 720 hours (30 days). The Dynamic Mechanical Analyzer (DMA) was used to measure the storage modulus and loss modulus of the substrate samples, from which the Elastic modulus was calculated. As anticipated, a decreasing pattern was observed in the calculated Elastic modulus as the temperature ranged from -35°C to 200°C for all cases. Interestingly, for the samples aged at 125°C, it was observed that the immersed samples exhibited lower elastic modulus values compared to the samples exposed to air. However, for the samples aged at 85°C, the elastic modulus of the air-exposed samples was higher than that of the immersed samples.[1][2] To comprehend the inversion in elastic modulus trends observed between the samples aged at 85°C and 125°C, further analysis is required. The study provides valuable insights into the changes in material properties of non-halogenated substrates when immersed in dielectric fluids such as EC100 and PAO6, and their impact on the reliability of electronic packages. The experimental data clearly indicates a decrease in Young's modulus for the thermally aged samples, resulting in a reduced number of cycles to failure and, consequently, an increase in the reliability of electronic packages. Thus it is concluded that the immersion of samples in dielectric fluids has a significant impact on the thermo-mechanical properties of the substrate.[1-5] The reliability of the samples is determined based on the modulus values, where higher values indicate a stiffer sample. Conversely, lower modulus values imply reduced stiffness and, consequently, less warpage, which enhances the reliability of the sample. The decrease in substrate stiffness after immersion in the dielectric fluid can be attributed to fluid absorption. Since there is limited literature available on immersion cooling from a reliability perspective, there is ample room for future research in this field, as the reliability of electronic packages is crucial for fully utilizing advanced technologies. Further studies can be conducted on this substrate with different dielectric fluids commonly used in industries for data center cooling to assess their thermomechanical properties. Additionally, the effects of increased time periods and temperatures can be investigated to understand their influence on the thermomechanical properties of the substrate. The data obtained from the dynamic mechanical analyzer can be utilized as input for finite element analysis (FEA) models, enabling simulations to study substrate failure computationally. Furthermore, delamination studies can be conducted on non-halogenated substrates, as it is a common type of substrate failure. [1-5]

REFERENCES

[1] Rabin Bhandari, A. L. (2022). IMPACT OF IMMERSION COOLING ON THERMOMECHANICAL PROPERTIES OF NON-HALOGENATED LOW CTE BT SUBSTRATE CORE . InterPACK2022. California.

[2] T. Chauhan, R. Bhandari, K. B. Sivaraju, A. S. M. R. Chowdhury, and D. Agonafer, “IMPACT OF IMMERSION COOLING ON THERMOMECHANICAL PROPERTIES OF LOW-LOSS MATERIAL PRINTED CIRCUIT BOARDS,” J. Enhanc. Heat Transf., vol. 28, no. 7, pp. 73–90, 2021.

[3] S. Ramdas, P. Rajmane, T. Chauhan, A. Misrak, and D. Agonafer, “IMPACT OF IMMERSION COOLING ON THERMO-MECHANICAL PROPERTIES OF PCB’S AND RELIABILITY OF ELECTRONIC PACKAGES,” presented at the ASME 2019 International Electronic Packaging Technical Conference and Exhibition, Anaheim, California, Dec. 2019

[4] S. Dhandarphale, “MEASUREMENT OF CHANGE IN CTE OF PCBS DUE TO SINGLE PHASE IMMERSION COOLING AND IMPACT OF CHANGED PROPERTIES OF PCBS ON SOLDER JOINT RELIABILITY OF BGA PACKAGE,” The University of Texas at Arlington, Arlington, Texas, 2020.

[5] J. Cho, T. Lim, and B. S. Kim, “VIABILITY OF DATACENTER COOLING SYSTEMS FOR ENERGY EFFICIENCY IN TEMPERATE OR SUBTROPICAL REGIONS: Case study,” Energy Build., vol. 55, pp. 189–197, Dec. 2012, doi: 10.1016/j.enbuild.2012.08.012

[6]S. B. S. R. Shrivastava S, "Comparative Analysis of Different Data Center Airflow Management Configurations," in ASME InterPACK, San Francisco, CA, 2005

[7] Advanced Cooling Technologies “Liquid Cold Plates” [online] Available: https://www.1-act.com/products/custom-cold-plates/

[8] Data Center Frontier- dielectric Fluid Immersion Cooling [online]Available: https://www.datacenterfrontier.com/cooling/article/11428163/grc-pushes-density-limits-with-support-for-200-kw-immersion-racks

[9]“Immersion Cooling for Green Computing, OCP SUMMIT,” (San Jose, California, 2018.)

[10] 3m “ immersion cooling for data center” 3m.com [online]Available: https://www.3m.com/3M/en_US/data-center-us/applications/immersion-cooling/

[11] R.Dandamudi “CFD ANALYSISOF THERMAL SHADOWING AND OPTIMIZATION OF HEAT SINKS IN 3RD GENERATION OPEN COMPUTE SERVER FOR SINGLE PHASE IMERSION COOLING APPLICATIONS” The university of Texas at Arlington, Arlington,Texas,2018.

[12] Nugroho Agung Pambudi, Alfan Sarifudin, Ridho Alfan Firdaus, Desita Kamila Ulfa, Indra Mamad Gandidi, Rahmat Romadhon “The immersion cooling technology: Current and future development in energy saving” Alexandria Engineering Journal, Volume 61, Issue 12,2022, https://doi.org/10.1016/j.aej.2022.02.059

[13] Single Phase Immersion cooling – AKCP.com[online] Available: https://www.akcp.com/articles/different-approaches-to-immersion-cooling/

[14]"Comparison Between Data Center Liquid Cooling Solutions"- Paolo Bianco

[15] Schematic diagram of two phase immersion cooling- Liard thermal systems[online] Available: https://lairdthermal.com/thermal-technical-library/application-notes/heat-exchangers-for-todays-immersion-cooling-systems

[16] Chowdhury, A S M Raufur & Rabby, Monjur Morshed & Kabir, Mehzabeen & Das, Partha Pratim & Bhandari, Rabin & Raihan, Rassel & Agonafer, Dereje. (2021). A Comparative Study of Thermal Aging Effect on the Properties of Silicone-Based and Silicone-Free Thermal Gap Filler Materials. Materials. 14. 3565. 10.3390/ma14133565.

[17] HITACHI, "Principle of Dynamic Mechanical Analysis (DMA) [online] Available:https://hha.hitachi-hightech.com/en/product-range/products/thermal-analyzer-series/dynamic-mechanical-analyzer-dma

[18]"Principle of Dynamic Mechanical Analysis (DMA) : Hitachi High-Tech GLOBAL." [online] Available: https://www.hitachihightech.com/global/products/science/tech/ana/thermal/descriptions/dma.html (accessed Feb. 03, 2021).

[19] " Hitacho DMA brochure" – alfatest.it [online] Available : https://www.alfatest.it/keyportal/uploads/hitachi-dma-brochure-web.pdf

[20] isola – IS550H Non-Halogenated Substrate [online] Available: https://www.isola-group.com/pcb-laminates-prepreg/is550h-laminate-prepreg/

[21] Ramdas, Shrinath & Rajmane, Pavan & Chauhan, Tushar & Misrak, Abel & Agonafer, Dereje. (2019). Impact of Immersion Cooling on Thermo-Mechanical Properties of PCB's and Reliability of Electronic Packages. 10.1115/IPACK2019-6568.

[22] Lakshminarayana, Akshay & Misrak, Abel & Bhandari, Rabin & Chauhan, Tushar & Chowdhury, A S M Raufur & Agonafer, Dereje. (2020). Impact of Viscoelastic Properties of Low Loss Printed Circuit Boards (PCBs) on Reliability of WCSP Packages Under Drop Test. 10.1109/ECTC32862.2020.00353.

[23] Ramdas, Shrinath & Chowdhury, A S M Raufur & Lakshminarayana, Akshay & Bhandari, Rabin & Chauhan, Tushar & Misrak, Abel & Agonafer, Dereje. (2019). Impact of Accelerated Thermal Aging on Thermo-Mechanical Properties of Oil-Immersed FR-4 Printed Circuit Boards.

[24] Misrak, Abel & Chauhan, Tushar & Bhandari, Rabin & Chowdhury, A S M Raufur & Lakshminarayana, Akshay & Mirza, Fahad & Gholami Bazehhour, Benyamin & Vujosevic, Milena & Agonafer, Dereje. (2021). Impact of Die Attach Sample Preparation on Its Measured Mechanical Properties for MEMS Sensor Applications. Journal of Microelectronics and Electronic Packaging. 18. 21-28. 10.4071/imaps.1234982.

[25] Misrak, Abel & Chauhan, Tushar & Rajmane, Pavan & Bhandari, Rabin & Agonafer, Dereje. (2020). Impact of Aging On Mechanical Properties of Thermally Conductive GAP Fillers. Journal of Electronic Packaging. 142. 10.1115/1.4045157.

[26] Modi, H, Shahi, P, Sivakumar, A, Saini, S, Bansode, P, Shalom, V, Rachakonda, AV, Gupta, G, & Agonafer, D. "Transient CFD Analysis of Dynamic Liquid-Cooling Implementation at Rack Level." Proceedings of the ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems. ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems. Garden Grove, California, USA. October 25–27, 2022. V001T01A012. ASME. https://doi.org/10.1115/IPACK2022-97443

[27] Shalom Simon, V, Modi, H, Sivaraju, KB, Bansode, P, Saini, S, Shahi, P, Karajgikar, S, Mulay, V, & Agonafer, D. "Feasibility Study of Rear Door Heat Exchanger for a High Capacity Data Center." Proceedings of the ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems. ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems. Garden Grove, California, USA. October 25–27, 2022. V001T01A018. ASME. https://doi.org/10.1115/IPACK2022-97494

[28] Rahangdale, U., Rajmane, P., Doiphode, A., Sakib, A.R., Misrak, A., Lohia, A.K., & Agonafer, D. (2017). Damage progression study of 3D TSV package during reflow, thermal shocks and thermal cycling. *2017 16th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 1119-1125.

[29] P. Rajmane, K. Dhandapani, M. Schwarz and A. Syed, "Investigation of the Factors Affecting the Warpage Prediction of Multi-Chip Package," *2021 IEEE 71st Electronic Components and Technology Conference (ECTC)*, San Diego, CA, USA, 2021, pp. 1514-1520, doi: 10.1109/ECTC32696.2021.00240

[30]Gandhi, Dhruvkumar, Uschas Chowdhury, Tushar Chauhan, Pratik Bansode, Satyam Saini, Jimil M. Shah, and Dereje Agonafer. "Computational analysis for thermal optimization of server for single phase immersion cooling." In International Electronic Packaging Technical Conference and Exhibition, vol. 59322, p. V001T02A013. American Society of Mechanical Engineers, 2019.

[31] Chinthaparthy, Lochan Sai Reddy. 2021. Accelerated performance degradation of single-phase cold plates for direct-to-chip liquid cooled data centers. Ph.D. diss., The University of Texas at Arlington, https://login.ezproxy.uta.edu/login?url=https://www.proquest.com/dissertations-theses/accelerated-performance-degradation-single-phase/docview/2640031815/se-2 (accessed May 16, 2023).

Biographical Statement

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