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Reliability Considerations for Oil Immersion-Cooled Data Centers

The improved efficiency of mineral oil may offer simplicity in facility design compared to traditional air cooling and provide a means for cost savings. Despite its improved cooling efficiency and cost savings, a mineral oil immersion cooling technique is still not widely implemented and original equipment manufacturers are reluctant to jeopardize sales of existing air-based cooling system equipment. Only compelling physics regarding thermal performance of direct immersion cooling is not enough for data center operators. Many uncertainties and concerns persist regarding the effects of mineral oil immersion cooling on the reliability of information technology (IT) equipment both at the component and chassis level. This paper is a first attempt at addressing this challenge by reviewing the changes in physical and chemical properties of IT equipment materials like polyvinyl chloride (PVC), printed circuit board (PCB), and capacitors and characterizes the interconnect reliability of materials. The changes in properties of a mineral oil like kinematic viscosity and dielectric strength are also cited as important factors and discussed briefly. The changes in mechanical properties like elasticity, hardness, swelling, and creep are being shown in the paper for thermoplastic materials. The chemical reaction between material and mineral oil as a function of time and temperature is also conferred. The literature gathered on the subject and quantifiable data gathered by the authors provide the primary basis for this research document. [DOI: 10.1115/1.4042979]

Keywords: information technology equipment, reliability, compatibility, reliability enhancements, immersion cooling

1 Introduction

Submerging servers and information technology (IT) equipment in a mineral oil, a dielectric liquid, enables substantial energy savings today and accommodates growing load densities of future facilities. The existing proprietary submersion cooling solutions [1,2] and numerous case studies [3] have established the effectiveness and energy savings for a new construction or a retrofit from device to the facility level. For mission critical operations of a data center, a comprehensive study of reliability and availability is necessary for widespread adoption of any disruptive technology [4,5].

Figure 1 provides an overview of the working of oil-cooled data centers [6], which eliminates the root causes of failures, improves the operating conditions and reliability and advances in cooling technology for data center industries. This technology paves the path for the retrofitting of air-cooled data centers and efficient performance with high-load capacities.

Oil immersion cooling technology of data centers extends the prospects for improved reliability in operations as it minimizes common operational issues and eliminates the root causes of failure like reduction in solder joint failures, lower operating temperatures for board and components, no oxidation/corrosion of electrical contacts, no moving parts, like fans, within the device enclosure, no exposure to electrostatic discharge, no sensitivity to ambient particulate, humidity, or temperature conditions. The reliability advances include a reduction in corrosion and electrochemical migration, lessening of environmental contamination like dust, debris, and particulates, and mitigation of tin and zinc whiskers [7,8].

Electrochemical migration is the movement of metal through an electrolytic solution under an applied electric field between conductors which are insulated. Electrochemical migration is a common reliability issue that can be found in the electronic packaging industry, including different materials and components like dies surface, epoxy encapsulates, printed circuit board (PCB), passive components, etc. The major electrochemical migration drivers are temperature, moisture, contamination, and voltage/electrical field. Immersion oil cooling reduces and/or eliminates temperature, moisture, and contamination aspects. The main sources of contamination are storage and environment. The concerns of storage include cleaning chemicals, outgassing, and polymeric materials. Operating environments include dust, debris, zinc whiskers, moisture, evaporated seawater and industrial pollutants like sulfur, etc. Oil immersion cooling prevents contamination accumulating. Efficient handling methods and cleanliness should be implemented and filtration of oil lessens the risk of particulate and dust contaminants. The constant operation proves the thermal stability of oil-cooled data centers. It is expected to see a hot spot reduction and improved thermal uniformity using immersion oil cooling. Tin whiskers are hair-like single crystal metallic filaments that grow from Tin films. The

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Contributed by the Electronic and Photonic Packaging Division of ASME for publication in the Journal of Electronic Packaging. Manuscript received June 20, 2018; final manuscript received February 15, 2019; published online April 10, 2019. Assoc. Editor: Baris Dogruoz.

potential failure modes are direct contact that causes an electrical short (arching) and requires growth of adequate length and in the correct direction. Electromagnetic radiation which releases or receives electromagnetic signal and noise at higher frequencies and deterioration of signal for frequencies above 6 GHz, which is independent of whisker length and debris like whisker breaks off and shorts two leads (primarily during handling). These can be mitigated by immersion oil cooling [7].

The problem in immersion cooling is when the whiskers break free, they become airborne and can circulate freely throughout the facility and get blown into the equipment, causing absolute mayhem without you even knowing. By using the pump system that has a layered filtering system, these little whiskers can be captured. Filtering in fluids is far easier than in air as the fluid restrains the filaments from floating free, and the filaments are drawn into the circulating pumps and can be filtered in one location.

Another important advantage of oil immersion cooling is that this form of cooling offers the opportunity to remove heat directly from the chip(s) and all other components with no intervening thermal conduction resistance, other than that between the device heat sources and the chip surfaces in contact with the liquid as the fluid is dielectric unlike indirect cooling which can only be used to those components where cooling distribution units are attached and the server cannot be completely immersed to cool all the components as it uses conductive water as a working fluid.

A primary concern by data center industry professionals regarding mineral oil immersion techniques is the impact of the fluids on the long-term reliability of components and systems. By fully immersing a server in oil, a company may be voiding the warranty on their equipment and expose themselves to potential failure costs. Current industry data regarding the reliability of server systems after immersion in mineral oil suggest that there is no detrimental impact to components [2,8]. However, the remarks made in the literature are anecdotal, not providing detailed information or data, limiting their utility to the industry at large.

This study focuses on the reliability of servers and IT equipment when submerged in a mineral oil at the device level. Prolonged immersion of servers in mineral oil will onset a wear-out mechanism and upon cumulative damage can lead to component failure. Degradation of material property or component functionality is a result of fundamental mechanical, chemical, electrical, and thermal phenomena introduced due to changes in the typical operating environment. The superior heat carrying capacity of a mineral oil compared to air eliminates hot spots and produces less variation in temperature spatially and in time. The chemical interactions between the coolant and various components for an extended amount of time introduce lifecycle loads which are not observed in traditional air cooling.

The components considered in this investigation are cables, printed circuit boards, packages, and passive components. Complete immersion of a server is responsible to the device and component level reliability. With the concern of critical performance, cost, safety, and operating environment, the study of the reliability of these four categories of components becomes significant. The study of the change in the properties of a mineral oil like kinematic viscosity, flash point, and dielectric strength is also the subject of anxiety for the data center operators. These properties have the direct relation with the coolant efficiency, servicing costs, pumping power, operating cost, and facility design. It becomes critical to know about these changes as it keeps data centers functioning. Some standard methodologies have already been derived to measure the changes in properties of important components submerged in a mineral oil. But sometimes, it becomes hard to follow those standards because of their limitations as they are designed to test the reliability of the materials in an air-cooled environment [9–11].

This paper also leaves a scope for instituting design of experiments for determination of modeling parameters and a methodology which should be analogous to accelerated thermal cycling (ATC) and accelerated thermal aging, so that it can be accepted as a standard methodology to provide the reliability analysis of oil-cooled data center components and the coolant. The methodology should be proposed and adopted which can provide the reproducible results to determine the failure in oil cooling technology. The assumptions should be made for all the parameters which are important in the case of oil immersion cooling. The parameters like heat load, flow rate, inlet temperature, and placement and power levels of the components and volume of the oil should be considered to fix the temperature for the thermal overstress experiment.

2 Setup and Approach

The study undertaken and discussed below presents a look at the impact of mineral oil on server components. This includes high-level visual observations, microscopic observations made by sectioning server components, and a more detailed study of the change in material properties that result from exposure of PCBs to mineral oil. Similar observations of air cooled servers were taken as a basis for comparison.

2.1 Effect of a Mineral Oil on Active Components Like Printed Circuit Boards and Packages. A sample of three servers that were immersed in a mineral oil for a six-month period during thermal testing was taken apart, photographed, and sectioned for imaging to document the effects of oil on server components. Figure 2 shows the fading of oil immersed screen-printed component markings on the memory chips of the dual in-line memory modules. Although not a direct impact on mechanical reliability, this fading of markings may impact identification of components when servicing is needed [12–14].

A more detailed visual study was carried out by taking cross section of various components to determine the microstructure of electronic packages. Key components were placed in molding compound, sectioned, and polished. Control samples of servers that were not exposed to oil and used in traditional air-cooled-based testing underwent the same testing. The details of the package structure were observed under microscopes.

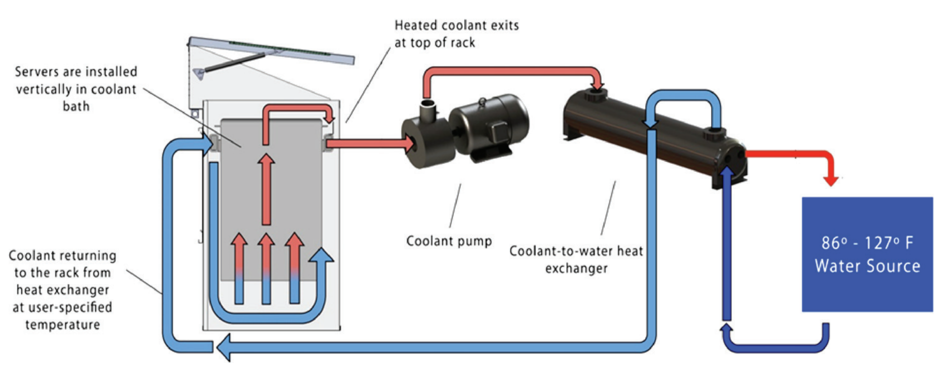


Fig. 1 Schematic of an oil cooled data center

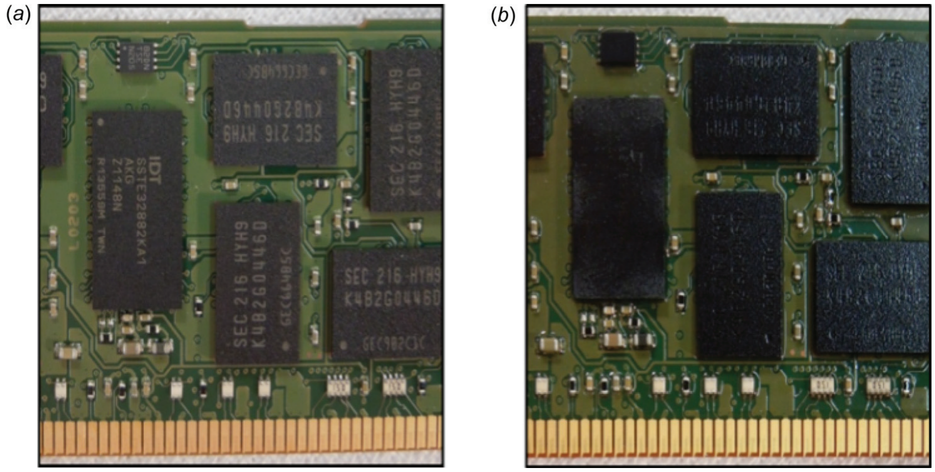


Fig. 2 Fading component identifies because of oil exposure was seen in: (*a*) an air-cooled server and (*b*) an oil immersed server

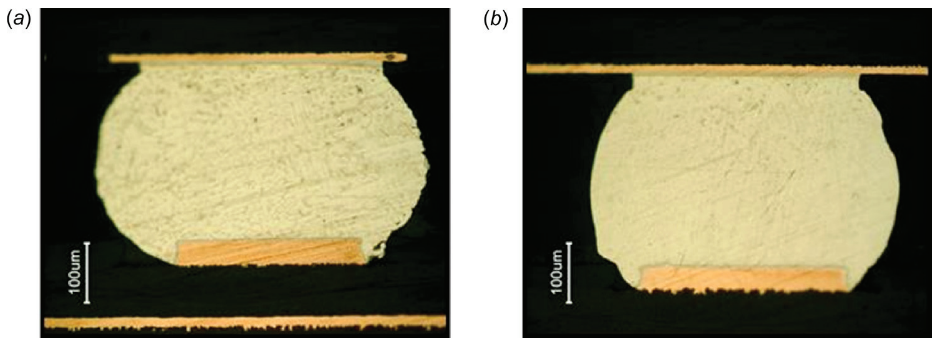


Fig. 3 Comparison of microstructure of solder balls taken from: (*a*) an air-cooled server and (*b*) an oil immersed server

Figure 3 offers a comparison of solder balls from the backside of the memory module attached to the dual in-line memory modules. As can be seen, there are no noticeable deformations, change in size, or cracking of solder balls. In addition, the intermetallic compound layers which provide the mechanical and electrical connection between PCB–solder balls and solder ball–substrate interfaces showed no change in thickness between air-cooled and oil-cooled samples. The chip underfill material, which strengthens the mechanical connection between a flip chip package and substrate, also showed no detectable variation between air- and oil-cooled samples. In Fig. 4, it is seen that there are no size variations in the metal layers of the packaging substrate. The trace thickness does not change or alter after exposure of the server in an immersive environment.

Additional samples of PCB boards showed no delaminating, swelling, or warpage of layers after extended periods of submersion in mineral oil. In Fig. 5, a cross section at a plated through hole location on the motherboard has maintained its structural integrity. Similar observations can be made from Fig. 6 at an edge location on the PCB.

The images and results gathered here provide a more detailed account to support the anecdotal claims made in the literature. In terms of component reliability, when submerging servers over the six-month duration, there is not any indicated reason for concern. However, typical servers operate in a data center for longer durations, anywhere from 3 years up to 10 years. A larger sample size of components and materials tested over extended periods or with

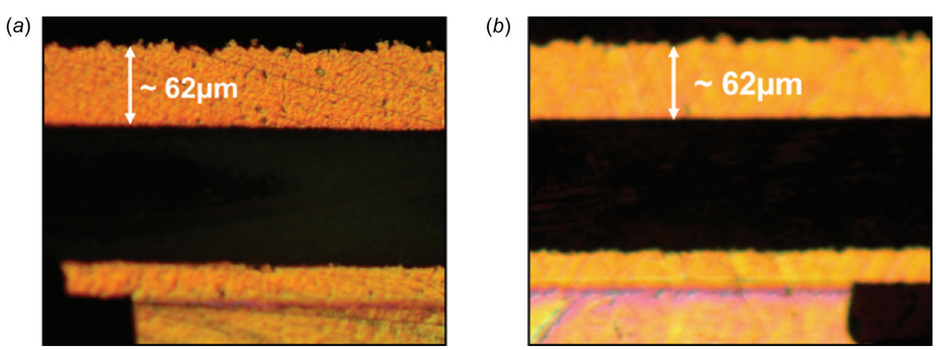


Fig. 4 Comparison of substrate layer of ball grid array package taken from: (*a*) an air-cooled server and (*b*) an oil immersed server

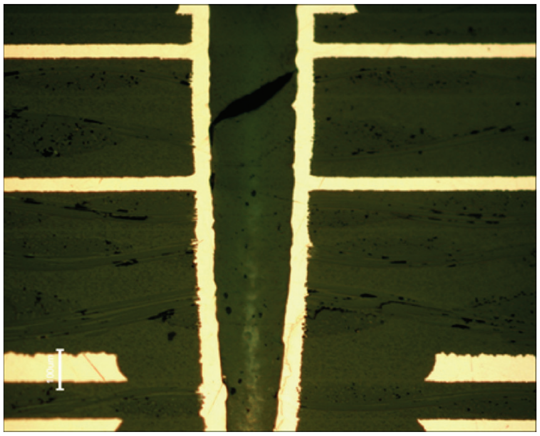


Fig. 5 Cross section of PCB plated through-hole on oil exposed server

Fig. 6 Edge of oil exposed PCBs maintain structural integrity and show no indication of delaminating

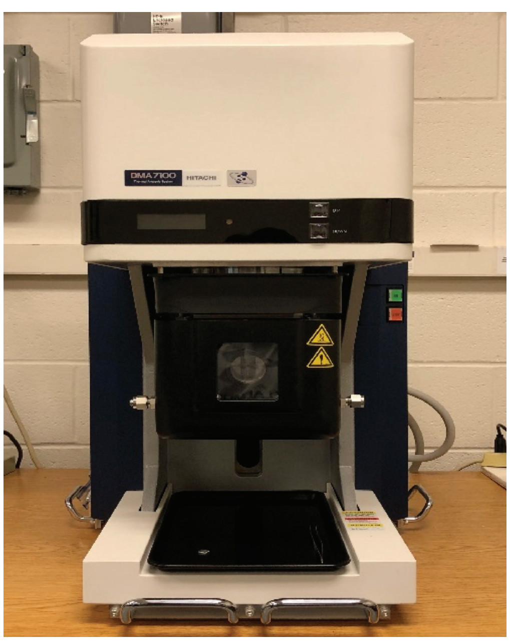


Fig. 7 Dynamic mechanical analyzer

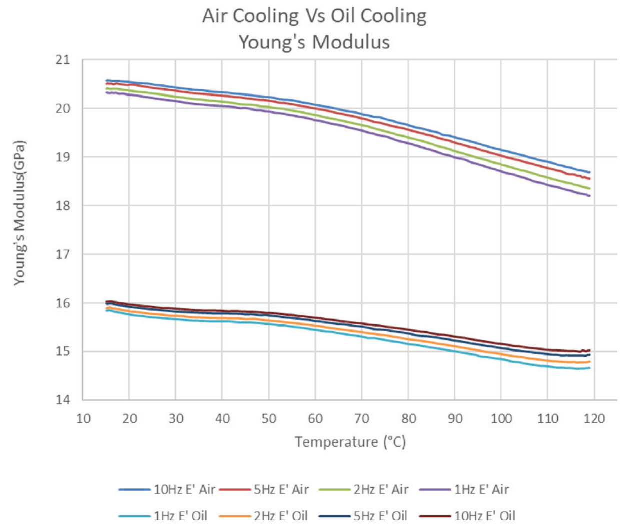


Fig. 8 Dynamic mechanical analyzer: PCB testing results

the aid of accelerated thermal testing can help strengthen the conclusions made here.

2.1.1 Dynamic Mechanical Analysis of a Printed Circuit Board Material. A study was initiated to determine the extent to which oil exposure alters the material properties of PCBs. Dynamic mechanical analysis measures the mechanical properties of materials as a function of time, temperature, and frequency. The term is also used to refer to the analyzer that performs the test (Fig. 7). Dynamic mechanical analyzer (DMA) is also called DMTA for dynamic mechanical thermal analysis. DMA works by applying a sinusoidal deformation to a sample of known geometry. The amount of deformation is related to its stiffness. A $10\,\text{mm} \times 50\,\text{mm}$ sample size was taken to measure elastic modulus from a temperature range from 15 °C to 120 °C. Samples were taken from the oil cooled server as well as the air-cooled server. The DMA measurement was performed at 1 Hz, 2 Hz, 5 Hz, and 10 Hz for both types of samples.

Preliminary strain measurements showed a significant decrease in Young's modulus of PCB material for servers that had been immersed in oil for an eight months period as compared to an air-cooled sample as shown in Fig. 8. A decrease of this type may severely improve the reliable life of a motherboard based on the trend discussed by Cheng et al. [15]. The results from this study may be input to finite element models to further simulate the impact of changes in material properties on the component and solder ball fatigue life [16]. The regression model can be created [17]. However, the physical observation showed stiffness in the PCB board.

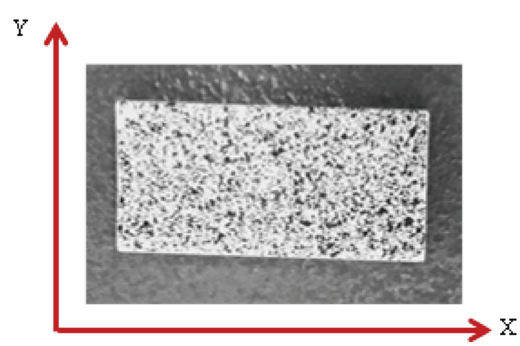


Fig. 9 Specked sample used for CTE experiment

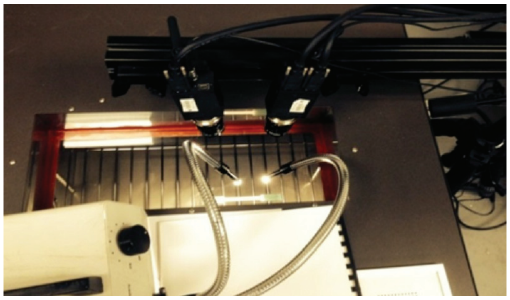


Fig. 10 Digital image correlation setup

2.1.2 Digital Image Correlation With Oven Testing for Coefficient of Thermal Expansion of Printed Circuit Board. A digital image correlation (DIC) technique was used to measure in-plane and out-of-plane coefficient of thermal expansion (CTE) of PCB. The samples were cut from the PCBs and then painted with white spray to get a good clear white background followed by black speckled spray paint which created several black dots on white paint as shown in Fig. 9. The working principle of DIC is that the cameras capture the movements of these black dots and measure the deformation in the specimen. Several readings were taken at different temperatures, i.e., 25 °C, 50 °C, 75 °C, 100 °C, and 125 °C. 5MP cameras were used with a DIC technique to monitor strain in the sample as it was heated from 25 °C to 125 °C. The sample was baked for 6–7 h before the experiments to remove the moisture.

Thermocouples were attached to the dummy sample which was kept near to original sample to monitor the temperature of the sample at various locations. Since the thermocouples are attached to the sample using thermal tape, there is a possibility that the tape might restraint the sample from free expansion during heating. Therefore, a JEDEC standard was followed and thermocouples were attached to the dummy sample and not on the test sample. The test setup is shown in Fig. 10 below.

The 20 channel data acquisition system was used to collect temperature data from thermocouples. Images at every 25 °C were captured using VICSNAP software provided with DIC system. Five megapixel high-speed cameras captured minute deformation in the specimen. Figure 11 shows the graph of strain versus temperature for an air-cooled and an 8 months oil immersed sample.

2.1.3 Printed Circuit Board Dielectric Constant and Dissipation Factor. The properties those define any dielectric material of PCB epoxies that influence high-speed circuit design, in terms of signal propagation delay and dissipation factor are:

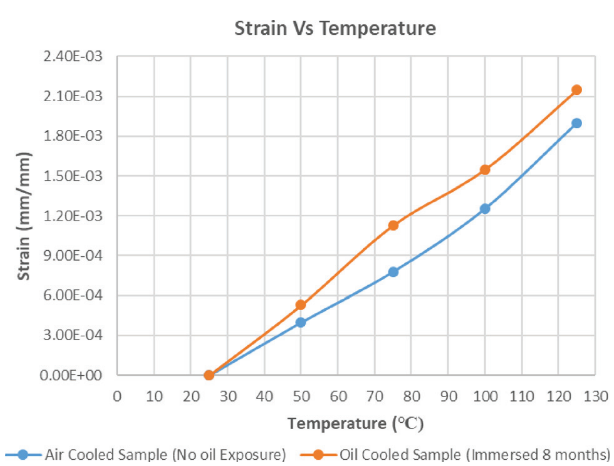


Fig. 11 Comparison of CTE of an air-cooled sample and an oil cooled sample

- dielectric constant and
- dissipation factor or loss tangent [18].

The propagation delay in ns/m is given in terms of effective dielectric constant by the relation

$$t_{pd} = 1.017\sqrt{\varepsilon_{\text{eff}}} \tag{1}$$

where ε_{eff} is the effective dielectric constant of the PCB epoxy. The increase in the dielectric constant due to water (available in the form of relative humidity, water, and gas contamination in a mineral oil) absorption increases propagation delay, that is, it slows down the speed at which the signal travels down the wire.

Dissipation factor or loss tangent $\tan(\delta)$ affects the insertion loss (attenuation) α, in terms of dB/in., of the signal as per the following relation:

$$\alpha = 2.3 * f * \tan(\delta) * \sqrt{\varepsilon_{\text{eff}}} \tag{2}$$

where f = frequency (GHz).

As the frequencies raise the GHz scale, more consideration must be paid to dielectric constant and the dissipation factor of the PCB epoxies. The PCB epoxies absorb moisture and will lead toward an increment in the values of both the dielectric constant and the dissipation factor, degrading signal speed and increasing the insertion loss. An oil immersion cooling technology provides more protection to the PCBs from direct exposure to humidity in the atmosphere [18].

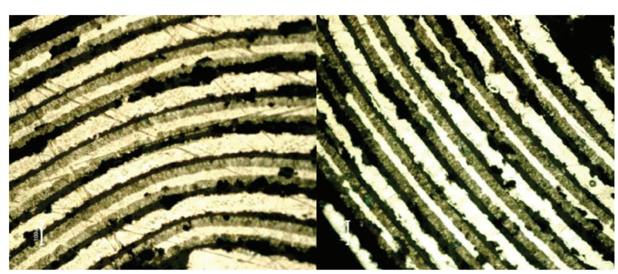
2.2 Effect of a Mineral Oil on Passive Components Like Capacitors. Electrolytic capacitors, prominently the aluminum conductive polymer capacitors, are generally used in servers. Degradation of performance in electrolytic capacitors can be caused by various factors like electrical, thermal, and environmental stresses. Upon electrical overstress, the increase in internal temperature, in turn, increases the electrolyte evaporation rate. Similarly, when the capacitor is operating or is stored in the high-temperature environment the heat travels from the body of the capacitor thereby increasing the internal temperature.

Capacitor degradation data in a thermal overstress experiment at 105 °C and humidity factor of 3.4% for 3500 h shown in Ref. [19]. Electrolytic capacitors and Polymer capacitors are mainly used in the data center industry and should be tested in mineral oil at elevated temperatures as provided for air cooling testing in Ref. [19].

Degradation of capacitors, in turn, leads to an implication in two main electrical parameters of the capacitor:

(1) equivalent series resistance and
(2) capacitance (C).

The temperature profile of a server, when immersed in mineral oil, reduces hot spots and ΔT across the servers and, therefore, provides a better operating environment for capacitors. The concern in mineral oil is about the dissolution of the electrolyte in



(*a*) (*b*)

Fig. 12 Comparison of microstructure of capacitors taken from: (*a*) an air-cooled server and (*b*) an oil immersed server

Fig. 13 Electrical cables and wiring

Fig. 14 Network cables

mineral oil causing degradation in the performance. Rubber bungs at the bottom and plastic capacitor sleeve should be avoided due to incompatibility with mineral oil. A degradation of capacitance should indicate any decrease in electrolyte volume of the capacitor. Liquid electrolyte capacitors that produce hydrogen gas when it fails due to the chemical reaction inside can be a cause of concern as well.

Figure 12 offers a comparison of the microstructure of capacitors. As can be seen, there are no noticeable deformations and/or changes between an air-cooled server sample and an oil-immersed server sample.

2.3 Effect of a Mineral Oil on Cables and Switching Devices. An observation made when handling servers after submersion in mineral oil for extended periods is that some materials become noticeably stiffer. This includes the plastic and insulating materials used for connection cords for power, networking, and hard disk drives. A concern among industry professionals is that this hardening may lead to cracking of insulators, exposing wiring or full failure of connectors.

The properties of insulation materials can be characterized as extruded primary insulations, which are applied directly over the conductor and are also used for jackets. As shown in Figs. 13 and 14, those are mainly polyvinyl chlorides (PVCs), polyethylene, fluorocarbons, and silicones. While PVC insulation has desired mechanical and electrical properties and low cost, those make it a stronghold of the wire and cable industry, it presents environmental concerns. PVC contains halogen. PVC releases toxic gasses, smoke, and acids while burning that can be harmful to health and equipment. Cross-linked polyethylene (XLPE) is halogen-free but is not highly recyclable. These two materials are abundantly being used in the cable industry. Using newly developed polyphenylene ether (mPPE) alloy insulating material is halogen-free and recyclable, yet remains cost-effective and robust [20].

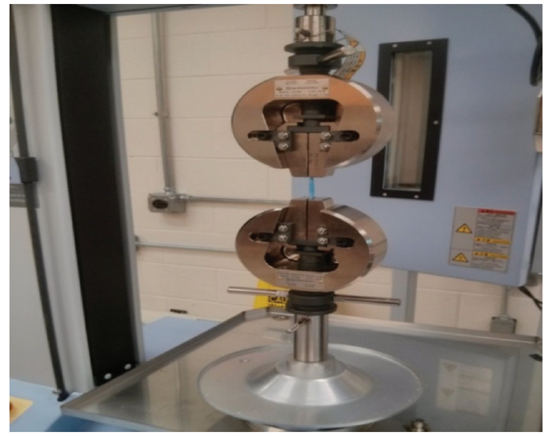


Fig. 15 Test setup to measure mechanical properties of cable specimen

There are different formulations of polyvinyl chloride which show extremely high- or low-temperature properties of PVC. Some PVC formulations have −55 °C to 105 °C rating. The regular PVCs have −20 °C to 60 °C. The dielectric constant is in between 3.5 and 6.5. XLPE has 150 °C ratings. Cross-linking converts polyethylene to a thermosetting material which enhances the properties of a material.

Rubber can be categorized as a natural rubber and styrene-butadiene rubber compounds. These materials can be used for both insulations and jackets purposes. Some formulations are suitable for 55 °C minimum, while others are suitable for 75 °C maximum.

Table 1 provides information regarding the properties of general insulation and jacket materials like oil resistance, resistant to heat, and dielectric strength based on the test results provided by different esteemed laboratories.

For a Mineral oil immersed rack or tank, the cabling architecture could comprise of a top of rack or end of row design like all modern data centers [21]. The servers are connected to the switch generally by an unshielded twisted pair cable for up to 10 GB/s for short distances. Off the shelf Category 5E, 24 AWG unshielded twisted pair local area network cable was considered for testing the impact of mineral oil. The cable is plenum rated and has a low smoke PVC jacket and fluorinated ethylene propylene insulation. As the thickness of the jacket specimen was less than 0.76 mm, the tubular specimen was prepared and tested in accordance with UL 2556. The specimen was 6 cm long and immersed in mineral oil for 48 h at 100 °C. The mechanical testing of the cable jacket specimen (the test setup has been shown in Fig. 15) was performed to determine the percentage change in elongation and to compare the change in Young's modulus.

From Fig. 16, it can be inferred that there is a drastic increase in Young's modulus. Due to aging in mineral oil, the specimen shrunk in length and loss of plasticizers could be attributed to its reduction in weight.

No performance impact of a mineral oil on RF components and switching devices has been found yet. No considerable analysis has been carried out yet. Operators have not detected any issues,

Table 1 Rating chart

Properties	PVC	PE cable	XLPE	mPPE	Rubber
Oil resistance	Fair	Excellent	Excellent	Excellent	Poor
Heat resistance	Good	Poor	Good	Good-excellent	Fair
Dielectric strength (kV/mm)	15–20	20	20	Not available	Not available

PE—polyethylene.

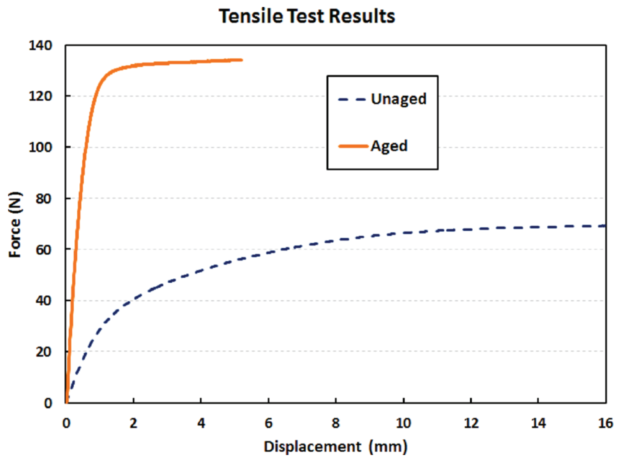


Fig. 16 Load versus extension for a low smoke PVC jacket tubular specimen without aging and aged in mineral oil

but to predict the life of materials and performance, the study should be acted upon.

An evaluation of optics in an oil-immersed server should also be carried out. How does oil impact signal and communication to and from a server? How would optics need to be packaged if oil is found to be a problem?

3 Changes in Properties of a Mineral Oil

The standard properties of mineral oil as per Data sheets/MSDS from STE Oil Company Crystal Plus Tech Grade Mineral Oil are

Density (kg/m^3)	849.3
Specific heat (kJ/kg·K)	1.670
Thermal conductivity (W/m·K)	0.13
Thermal expansions coefficient (1/K)	0.0007
Thermal diffusivity (m^2/s)	9.166×10^{-8}
Prandtl number (at 40 °C)	134.4 [22,23]

NOTE: Some of these properties may be temperature dependent (i.e., density). The changes in properties of a mineral oil are mainly concerned with the changes in kinematic viscosity and dielectric strength [22,23].

The viscosity of oils has a relationship with temperature and time, and it affects system pressure directly. So that pumping power becomes critical. A standard correlation between viscosity and temperature for transformer oils is given in Refs. [22] and [23] as

$$\mu = C_1 * \text{Exp}\left[\frac{2797.3}{T + 273.2}\right] \tag{3}$$

where, μ = dynamic viscosity (centipoise), T = temperature (°C), and C_1 = coefficient for scaling (Table 2).

Table 2 Analytical calculation of viscosity with respect to oil temperature [22,23]

Oil temperature (°C)	Dynamic viscosity μ (kg/m·s)	Kinematic viscosity ν (m^2/s)
30	0.01405	1.65×10^{-5}
35	0.01209	1.42×10^{-5}
40	0.01046	1.23×10^{-5}
45	0.00909	1.07×10^{-5}
50	0.00794	9.35×10^{-6}
55	0.00696	8.19×10^{-6}

The direct proportionality of viscosity with Reynolds number (Re) [24], Reynolds number with friction factor (f), and friction factor with pressure drop (Δp) for laminar flow is given below as [22,23]:

$$\mu \propto \frac{1}{\text{Re}} \propto f \propto \Delta p \tag{4}$$

That results in the relation with the pumping power

$$P_{\text{pump}} = \Delta p * \bar{V} \tag{5}$$

where $\bar{V}$ = volumetric flow rate [22,23].

Figure 17 shows the experimental results which infer that the change in viscosity has a direct impact on pumping power. That may be useful to derive the flow rate and operating conditions. It has a direct relation with operating cost too.

Since pumping power and flow rate are directly related to the operating cost, critical performance and efficiency of facility equipment, to study the phenomena regarding the change in viscosity of a mineral oil for data center operators becomes significant.

Temperature, oxygen availability, and presence of a catalyst (thermal aging) are the main factors that influence the chemical stability of the oil. The hydrocarbon molecules in oil start to decompose at high temperature and that may cause the oil degradation process. The oxygen contents in cooling oil might lead to a rise of the acidity number and to sludge formation [25].

It is important to perform an accelerated thermal aging test for any hydrocarbon fluid before using it for immersion cooling of data centers. During an accelerated thermal aging process, it is also important to analyze the dielectric properties of mineral oil, such as the breakdown voltage, dielectric losses (tan A), and relative permittivity. There is some analysis carried out for transformer oil. The study of aging test for the transformer (mineral) oil concludes that there is a chance of a leak during the operation and its less biodegradable property leads toward pollution. This may create safety, serviceability, disposal, and maintenance-related challenges for mineral oil-cooled data centers. At the end of the aging process, the mineral oil demonstrated lower breakdown voltages rather than at the starting. The literature states breakdown voltage depends on water content, suspended particles, and cleanliness. The tan(δ) of a mineral oil showed the significant variation during the different stages of the aging test process. The dielectric strength of transformer oil (mineral oil) remains almost consistent across the temperature range of interest for data center applications (30–50 °C). However, the study of change in the dielectric properties of oil in transformers shows some

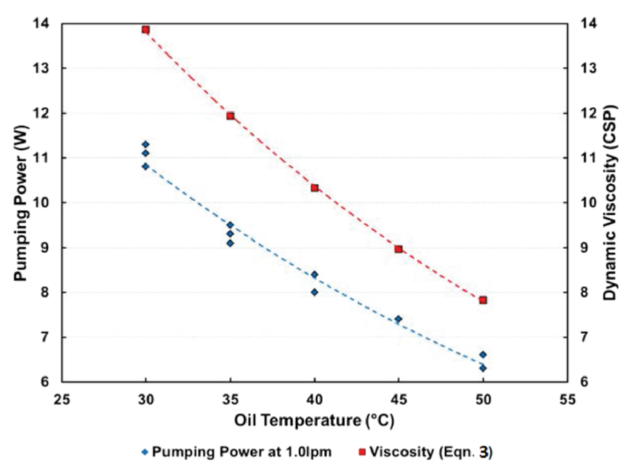


Fig. 17 The relationship between pumping power and temperature dependent dynamic viscosity

Fig. 18 Accelerated thermal cycling trial testing setup in environmental chamber

degradation over time. The effect of humidity should also be considered during the oil aging test [25,26].

Thus, the dielectric property analysis for the data center cooling mineral oil should be performed by proposing an aging test to provide the property variation data to data center operators for advancements in oil cooling technology and to increase its applicability [26]. It would be an interesting study to observe the change in kinematic viscosity and thermal conductivity of a mineral oil during the actual operation as a function of temperature and time. The comparative study of different engineered fluids should also be performed to provide more options to industries.

4 Accelerated Thermal Cycling Trial Testing

The Joint Electron Device Engineering Council (JEDEC) and the American Society of the International Association for Testing and Materials (ASTM) standards would not be relevant due to the significant difference in the ramp rates of air and oil. Failure mechanisms and models for IT equipment established by these standards are not directly applicable in the reliability analysis of oil-immersed components as oil immersion cooling has a different thermal profile and operating conditions than the air-cooled data centers for which these standards have been derived. International Electrotechnical Commission and International Organization for Standardization test methods might not have the direct applicability to determine the real degradation in the properties of a mineral oil as the oil-cooled data center has different parameters affecting the operation such as temperature, flow rate, varied surfaces, different materials, etc. The air-cooled system has a high fluctuation in operating conditions such as temperature and relative humidity. The standard also represents such variations in thermal cycling with high temperature differences. In oil cooling, the temperature profile is more stable and even. So, the standard also needs to be developed for such conditions and parameters should be modified accordingly. It is important to provide the design of experiment to perform reliability testing and evaluate the life cycle of oil cooled data centers.

The trial experiment (Fig. 18) was performed to determine feasibility of ATC tests on oil in the environmental chamber based on JEDEC standards.

- cycling test conditions (settings on environmental chamber);
- $T_{HI} = 100\,^{\circ}C$;
- $T_{LO} = 0\,^{\circ}C$;
- ramp rate = 10 °C/min;
- dwell time = 1 h; and
- oil volume = 1 gal.

Figure 19 shows the results of the trial test which was conducted to determine the feasibility of performing ATC tests on oil in the environmental chamber. Clearly, the ramp time and dwell times between air and oil are going to be significantly different. Thus, standards and common assumptions made for air cooling would not apply for immersion cooling lifecycle. Since it seems unlikely that accelerated cycling will be able to be tested in a timely manner, an alternative test is sought. Elevated temperature tests (thermal aging) can be used to gather some results for PVC, PCBs, and passive components. In this proposed method, we need to maintain a temperature above typical operating temperature for an extended duration. This type of test is common in capacitor degradation tests.

5 Conclusion and Future Work

The information furnished here is based on strong literature review and quantifiable data gathered for validation. This study provides a strong background for direct and indirect reliability concerns related to oil cooling technology. The operators will have trustworthy data to implement this technology.

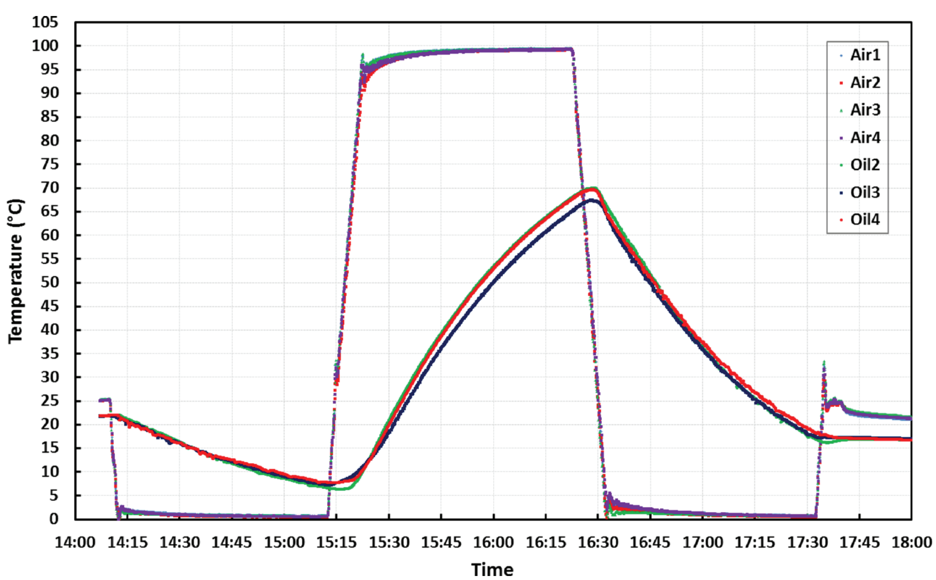


Fig. 19 Accelerated thermal cycling trial testing results

The issues associated with the mechanical reliability and operational service impact of adopting single-phase immersion cooling strategy must be addressed before the technology will see widespread adoption. The visual studies presented here indicate that certain compromises or adjustments in data center operation, such as inventory tracking and servicing procedures, will need to be made for this technology. From a structural point of view, no damage or alterations to components were observed from both the macro and microscopic views. However, changes in mechanical properties due to exposure of hydrocarbon fluids may alter the length of the useful life of components in fluids. Studies with an increased sample size and over multiple time durations help strengthen the findings presented above. Understanding the rate of change of material properties over extended service times may help build industry confidence in this technology and promote future adoption.

Oil immersion cooling may offer better practices in some developing countries like India, China, etc., where the environmental conditions for data centers are above ASHRAE G3 severity level and where it is hard to implement airside economizers to derive recommended environmental envelope. With the enhanced reliability, high heat dissipation and performance efficiency, oil cooling technology may serve the data center cooling technology world as a leader in the future.

As we can reiterate that the field of reliability for oil immersion cooling has a lot of scope for future work. The effects of mineral oil and/or different engineered fluids on major components should be measured. We are currently testing mineral oil, synthetic fluids like EC-100 (Engineered Fluids, Tyler, TX) and engineered fluids like Fluorinert™ and Novec™ (3M Company, St. Paul, MN) for electronics cooling and getting great results. The changes in electrical and chemical properties of mineral oil and fluids such as EC-100 should be investigated by an aging test. The humidity and contaminant barriers, especially leaching out from plastics of cables and components should be checked. The temperature and heat density optimization should be carried out. Thus, the scope of studying thermal performance and reliability concerns of oil immersion cooling technology is of all data center operators' interest and concern.

Funding Data

- NSF I/UCRC in Energy-Smart Electronic Systems (ES2) (Funder ID: 10.13039/501100008982).

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