OPEN Compute Project

Base Specification for Immersion Fluids

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December 1, 2022

Revision History

Revision	Version	Date	Comments
1.0	1.0	December 1, 2022	Initial Release

Contributors

Authors	Company
Sandeep Ahuja	Intel Corporation
Je-Young Chang	Intel Corporation
Kai Wang	Intel Corporation
Max Klemes	Intel Corporation
Jessica Gullbrand	Intel Corporation
Nishi Ahuja	Intel Corporation
Samantha Yates	Intel Corporation
Aravind Munukutla	Intel Corporation
Arpita Mitra	Intel Corporation
Jeff Pasternak	Intel Corporation
Mark Hemmeyer	Intel Corporation

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1. License

1.1 Open Web Foundation (OWF) CLA

1.2 Acknowledgements

The Contributors of this Specification would like to acknowledge the following OCP members for their feedbacks:

The Intel team wants to express a sincere thank you to the OCP immersion leadership of Punith Shivaprasad (Shell), John Bean (GRC), and Rolf Brink (Asperitas) for leading the detailed vetting of this specification with the OCP immersion community. Also, a special thank you to Jimil Shah (TMGCore), Mustafa Kadhim (Iceotope), Kevin Wirtz (Cargill), Gustavo Pottker (Chemours), Mark Miyoshi (Submer), Peter Cooper (Submer), Kai Zhou (UL), Ettore Parente (UL), Andy Young (Asperitas), Nick Schweissguth (LiquidStack), Amy Short (Lubrizol), Kathryn Oseen-Senda (Microsoft), Vaidehi Oruganti (Microsoft), Ashish Raniwala (Microsoft), Mark Shaw (Microsoft), Yangfan Zhong (Alibaba), Dan Liu (Alibaba). Zhichao Lv (ByteDance), Chen Wang (ByteDance), Yulong Wang (ByteDance), Pengfei Cheng (ByteDance), Chenglong Gui (ByteDance), Aimee Toney-Lovings (Intel), Rodel Samiley (Intel), Akshay Phadnis (Intel), Henry Peng (Intel), and Tina Bao (Intel) for providing support and detailed feedback on this specification.

2. Compliance with OCP Tenets

2.1 Openness

This fluid specification was developed in collaboration with industry experts both within and external to OCP. The specification is open to use by the community. The immersion cooling community will continue to build and evolve this specification as needed. Since this specification does not specify all the fluid parameters, but the Figure of Merits (FOMs), it leaves room for the fluid suppliers to innovate to develop more efficient and sustainable immersion fluids.

2.2 Efficiency

Immersion technology is an efficient cooling solution with the potential of ~100% heat reuse. An example of efficiency is the elimination of fans for cooling when going from air to immersion cooling. This results in significant efficiency improvements and a lower Power Usage Effectiveness (PUE) value compared to air.

2.3 Impact

This is the first open immersion fluid specification generated for cooling of both current and future IT equipment. This document will provide a base for further discussion, and Figures of Merits may be added and defined as needed to help guide fluid selection appropriate to the deployment.

2.4 Scale

The fluid specification eases immersion technology adoption and streamlines the supply chain. There are many immersion fluid choices in the industry today. This creates significant challenges for generating an immersion supply chain, which hampers adoption of immersion solutions.

2.5 Sustainability

This fluid specification targets the development of sustainable immersion fluids that meet the requirements of safety, regulatory compliance, low GWP (global warming potential), zero ODP (ozone depletion potential), low toxicity, low flammability, and with long operational lifetime.

3. Scope

This document defines the technical details for a base specification for a de-facto standard (new standard with no hardware product). Any supplier seeking OCP recognition for a hardware product based on this Specification must be 100% compliant with any and all features or requirements described in this Specification.

4. Overview

4.1 Introduction of Cooling Technologies

There are mainly two types of liquid cooling technologies that are being considered by the datacenter industry to drive energy efficient, sustainable datacenter. These technologies are:

- Cold plate
- Immersion

Each of these technologies can be either single-phase or two-phase as shown in Figure 1.

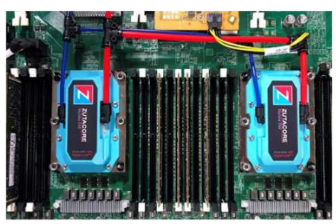
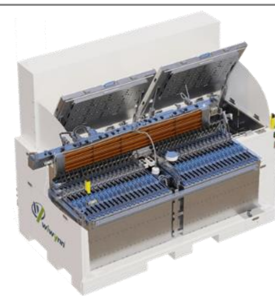
	Cold Plate Based	Immersion Based
Single Phase		
Two-Phase		

Figure 1: Cold Plate and Immersion Cooling Technologies from CoolIT[1], GRCooling[2], ZutaCore[3] and Wiwynn[4]

In single-phase immersion open bath tank applications, dielectric coolant in liquid state generally enters at the bottom of the tank, picks up heat from the servers and stays in liquid form as it leaves the tank to a CDU for cooling with facility water. If the open bath immersion solution relies on natural convection for the cooling, the liquid is circulated through the open bath, where the tank has a stratified temperature gradient with the coldest liquid in the bottom and warmest on the top. In a two-phase immersion case, the coolant boils at the boiling temperature (usually around 50 °C for IT equipment) and turns into vapor. The vapor rises in the tank and reaches condenser coils and turns into liquid and falls back down into the liquid in the open bath. Figure 2 shows additional example pictures of single-phase and two-phase immersion systems.

Figure 2: Examples of Immersion Systems: Top Row: Single-Phase Tank from GRC[5], Single-Phase Tank from Submer[6], Single-Phase Tank from Asperitas[7], Chassis Level Immersion System from Liquidcool[8] [9], Bottom Row: Two-Phase Immersion Tank from Wiwynn[10], Two-phase Immersion Tank from Liquidstack[11], Chassis level solution in a standard rack from Iceotope[12]

In addition to tank-based immersion systems, chassis level immersion systems have been developed in the industry that fit into standard racks.

This document focuses on immersion technology. It covers an immersion fluid requirement that meets thermal, signal integrity, material compatibility and reliability goals for the IT equipment.

4.2 Need for standardizing Immersion Liquids

One of the key differences between cold plate technology and immersion technology is that the liquid comes in direct contact with the IT equipment in the case of immersion. At present, there are a large number of liquids that are being used for both single- and two-phase immersion. Single-phase liquids can be categorized into four types: 1. Hydrocarbons 2. Fluorochemicals. 3. Natural esters 4. Synthetic esters. Two-phase liquids being used for immersion are mostly Fluorochemicals.

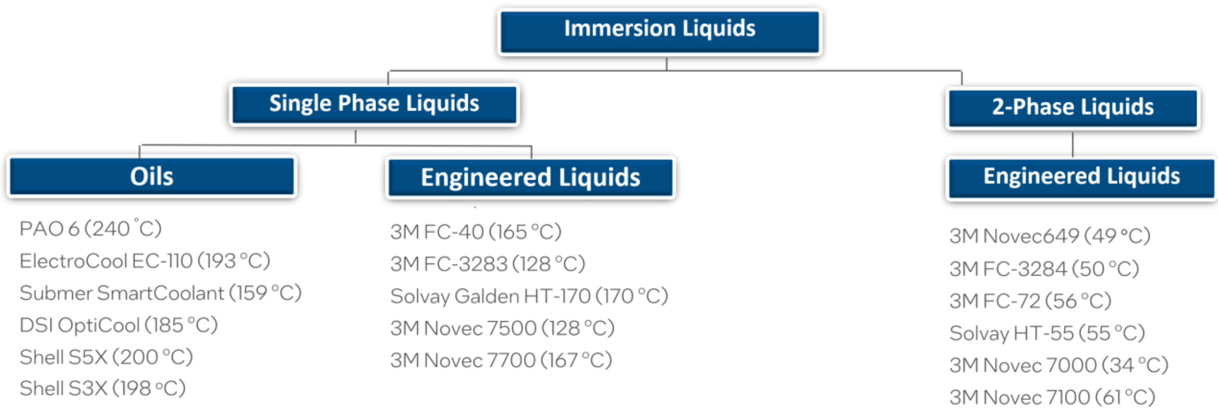


Figure 3: Examples of some Immersion Liquids

Given that immersion liquid comes in direct contact with IT equipment, server IT equipment manufacturers (OEMs & ODMs) and companies that provide server ingredients such as CPUs, GPUs, memory, mother boards, SSDs, cables, power supplies etc. have to ensure that their components are compatible with the immersion liquids. The challenge lies in the fact that there are a wide range of immersion liquids being used in the industry and it is almost impossible for all OEMs, ODMs and ingredient suppliers to ensure that their products are compatible with every liquid in the market. One also has to ensure that the product will work reliably over its design life of ~5yrs when immersed in the liquid.[13]

Validating compatibility and reliability of IT equipment with the liquid is quite cumbersome for the industry especially if one has to ensure compatibility with a large variety of liquids being used in the industry. Therefore, there is a need to standardize the liquid for the IT industry to use for datacenter cooling purposes. Everyone in the supply chain can ensure that their components are compatible with the standardized liquid. This way when servers and other IT equipment (e.g. switches) are being put together, they will be compatible with the fluid and will require less degree of validation.

5. Immersion Fluid Requirement

There are some key metrics that have to be specified for the liquid such that it meets requirements for:

- Thermal performance
- Signal Integrity performance
- Material compatibility & Reliability, Maintenance and Serviceability
- Environmental Impact

In this section, details around each of the performance metrics is given.

5.1 Thermal Performance Requirement

One of the key functions of the immersion liquid is to remove heat from the IT equipment. It needs to have very good heat removal capability such that it cannot only cool today's CPUs, GPUs, memory and other components that are designed for air cooling, but also future products that can take advantage of better cooling offered by liquid immersion cooling to deliver higher performance.

Datasheet for some of the immersion fluids can be obtained from the immersion fluid vendor websites.[14] [15]

Data sheets typically list each property individually. What one really cares about overall heat removal capability. Individual properties such as specific heat, conductivity, viscosity, and density are not that important when considering overall heat removal capability. Combination of these properties should be such that it results in better cooling capability. The combinations of fluid properties are called "Figures of Merit" in this document. Many properties of immersion fluids are strong functions of temperature. Therefore, liquid vendors should provide properties as a function of temperature and not just at a reference temperature.

5.2 FOM1 – Natural Convection for Single Phase Immersion:

Typically, heatsinks are used to remove heat from high power components such as CPU packages. The optimized geometric features of the heatsink (fin pitch, fin thickness etc.) can be different from the heatsinks that are used for air cooling. Servers are installed in an open bath tank vertically and length of heatsink fins is aligned vertically as well to allow for flow to rise as shown in Figure 4.

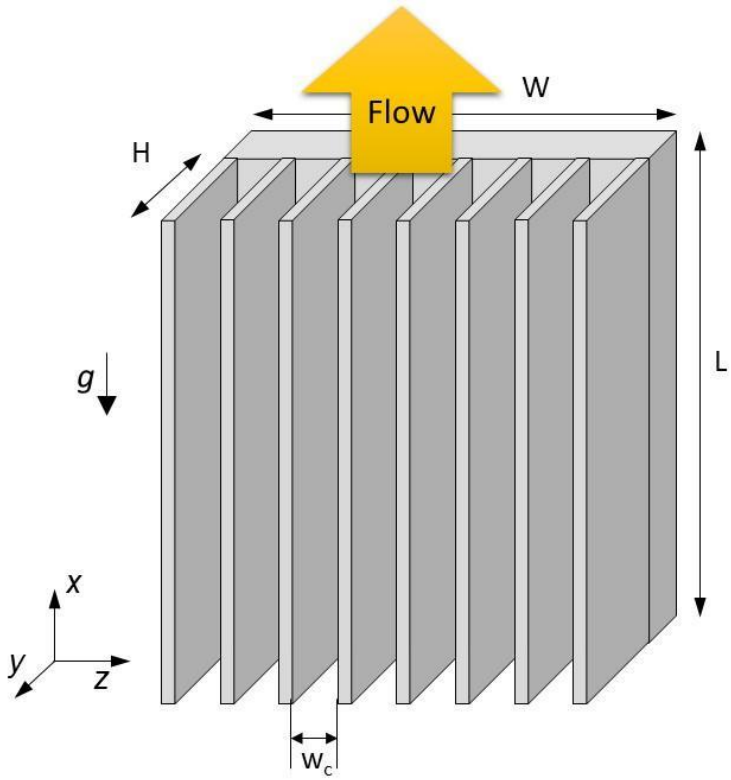


Figure 4: Natural Convection Flow Through an Immersion Heatsink

For natural convection, Nusselt number correlation of heatsink with vertically oriented plate-fins is considered[16]:

$$Nu_{fin} = [(0.09112El^{0.6822})^{-3.5} + (0.517El^{0.2813})^{-3.5}]^{-1/3.5}$$

where, $El = Elenbass\ number = \frac{g\ \beta(T_w - T_{amb})W_c^4}{L\upsilon^2}$

In the above correlation,

T_w: Wall temperature, °C

W_c: Channel width, m

T_{amb}: Fluid temperature entering at the bottom, °C

L: Length of the heatsink, m

υ: kinematic viscosity, m^2/s

β: Thermal expansion coefficient, 1/K

g: Gravity, m/s^2

Leveraging the above correlation:

$$Nu_{fin} = El^n$$

$$\text{h} = \frac{k}{L} El^n$$

$$= \frac{k}{L} (\frac{g\beta \Delta T \cdot Pr \cdot W_c^4}{L\nu^2})^n$$

The purpose of this exercise is to determine what fluid properties will improve heat transfer coefficient. Therefore, all geometry and temperature related parameters are dropped from the above equation.

$$\approx k (\frac{\beta Pr}{\nu^2})^n$$

$$\approx k (\frac{\beta c_p \rho^2}{\mu k})^n$$

Therefore, the Figure of Merit for natural convection can be defined as:

FOM for natural convection (FOM1) = $k (\frac{\beta c_p \rho^2}{\mu k})^n$ where n=0.2813

where:
k= thermal conductivity [W/m-K]
β= thermal expansion coefficient (1/K)
c_p = specific heat [J/kg-K]
ρ = liquid density [kg/m^3]
μ = liquid dynamic viscosity [N-s/m^2]

The above figure of merit is evaluated for many available fluids in the market and is plotted in Figure 5. Majority of 3rd Generation Intel® Xeon® Scalable Processors that require 2U servers for air cooling can be cooled in 1U with immersion if the above figure of merit is better than 35 provided coolant temperature entering the heatsink is below 40 °C. However, there are some high-performance Xeon processors that have stringent temperature specifications aligned with cold plate-based liquid cooling capability. In order to meet temperature specification of such processors, a better immersion liquid is needed.

The immersion fluid spec for FOM1 is set as:

FOM1 = 35, Tier 1 single-phase immersion liquid, and
FOM1 = 45, Tier 2 single-phase immersion liquid

Note that FOM1 values listed above are based on fluid properties in SI units as listed above. If there is a trade-off between cost and thermal performance, the end user should consider if the thermal performance can be met with Tier 1 liquid. If this is indeed the case, consideration should be given to choose Tier 1 liquid. However, if the liquid is planned to be used for more than one generation of servers, consideration should also be given if the future cooling requirements are likely to grow. If that is the case, the end user may choose to select Tier 2 liquid at the beginning of the installation. Note that Tier 3 with a higher FOM1 may be added in a future specification. Higher values of FOM1 are preferred for better thermal performance.

It should be noted that case-to-liquid thermal resistance is made up of conductive and convective portions and can be written as:

$$\Psi_{cl} = \Psi_{cond} + \Psi_{conv}$$

$$\text{or}\ \ \Psi_{cl} = \Psi_{cond} + 1/hA$$

where

Ψ_{cond}: Conductive portion of the heatsink resistance and represents flow of heat through thermal interface material and heatsink base and fins.
Ψ_{conv}: Convective portion of the heatsink at the surface of the heatsink.
h: Average heat transfer coefficient on the heatsink surface, W/m^2-K
A: Surface area of the heatsink, m^2

Optimized heatsink design can be different for different immersion liquids. For lower viscosity liquids, one can use more fins and get a higher heat dissipation area and minimize the thermal resistance value. Therefore, heatsink optimization for single phase immersion along with server layout should be taken into consideration. Many servers today use heatsinks designed for air cooling for immersion as well. These heatsinks are not well suited for viscous oils to flow easily through them. One can optimize heatsink for immersion application without incurring any additional cost for the heatsink. This along with choice of spreadcore vs. shadowed system layout can significantly affect cooling capability that can be achieved for a given liquid. Figure 1, the top left picture is that of a shadowed system. The bottom left picture is for a spreadcore system.

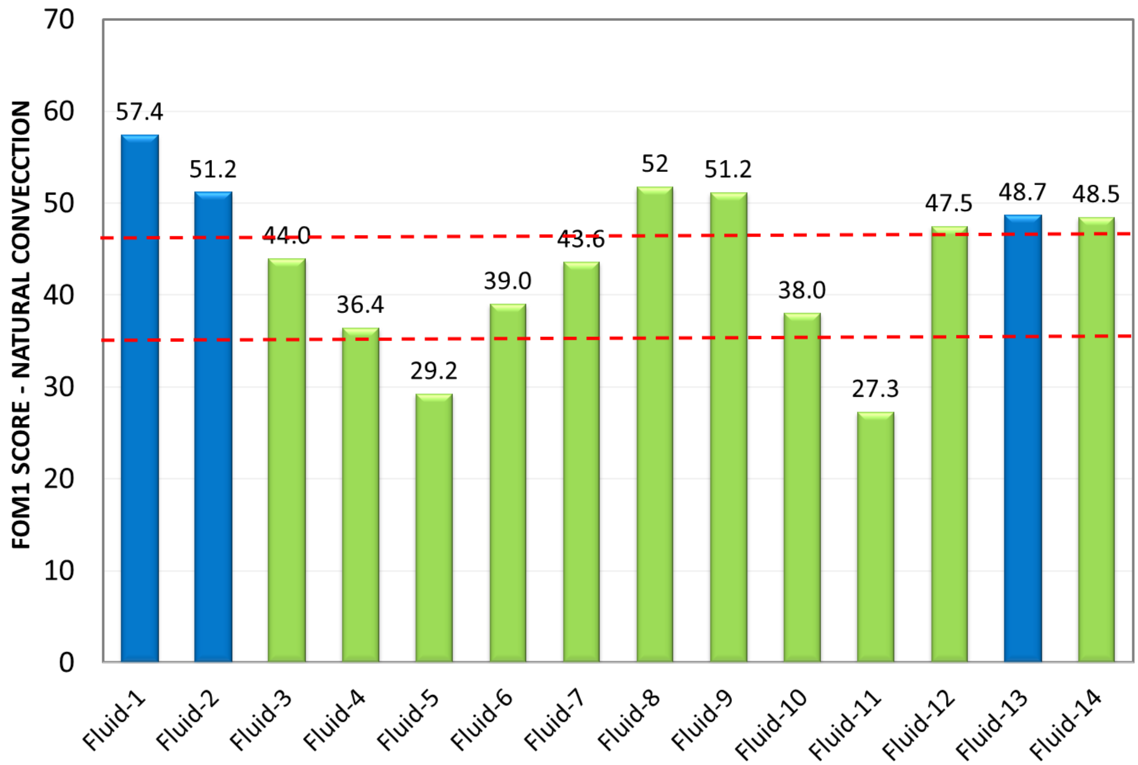


Figure 5: FOM1 Representing Natural Convection Effectiveness for Many Immersion Liquids (Higher FOM1 is thermally better)

The blue bars are for fluorochemical liquids, and the green bars represent hydrocarbon based liquids along with other types of liquids.

Note that FOM1 is currently evaluated using properties at 25 °C. The reference temperature for evaluating FOM1 will be changed to 50 °C to reflect a temperature more closer to actual use temperature. The only reason for choosing 25 °C for this initial release is that data for most liquids is available at 25 °C. However, liquid vendors should provide the data at 25 °C, 30 °C, 40 °C, 50 °C, 60 °C and 70 °C. Once liquid vendors start providing property data as a function of temperature covering the above stated temperature values, it will be easier to move the reference temperature to 50 °C along with a different spec value. Note that material properties of liquids can change significantly with temperature by different amounts. Relative FOM1 values for different liquids can be different at 50 °C than what is observed at 25 °C.

5.3 FOM2: Forced Convection Figure of Merit for Single Phase Immersion

For forced convection, the following correlation for developing laminar flow through pipes is used[17].

$$Nu_D = 1.86\left(\frac{Re_D Pr D}{L}\right)\left(\frac{\mu_b}{\mu_w}\right)^{0.4}$$

where:

Re= Fluid Reynolds number based on heatsink channel width
Pr= Fluid Prandtl number based on heatsink channel width
L= Heatsink length [m]
μ_b= dynamic viscosity of the fluid in the bulk [N-s/m^2]
μ_w= dynamic viscosity of the fluid next to the wall [N-s/m^2]

Thermal boundary conditions for immersion application are neither uniform wall temperature nor uniform wall flux. The flow is going to develop laminar flow. The last correlation is best suited for deriving Figure of Merit (FOM2) for laminar flow.

$$h \sim k \left[\frac{\rho\, C_p}{k}\right]^{1/3}$$

$$\mathrm{FOM2} = \mathrm{k} \left[\frac{\rho\, \mathrm{C_p}}{\mathrm{k}}\right]^{1/3}$$

where:

ρ: Density, kg/m^3
k: Thermal conductivity, W/m-K
C_p: Specific Heat, J/kg

The figure of merit was evaluated for many immersion liquids and is plotted in Figure 6. The blue bars are for fluorochemical liquids, and the green bars represent hydrocarbon based liquids along with other types of liquids.

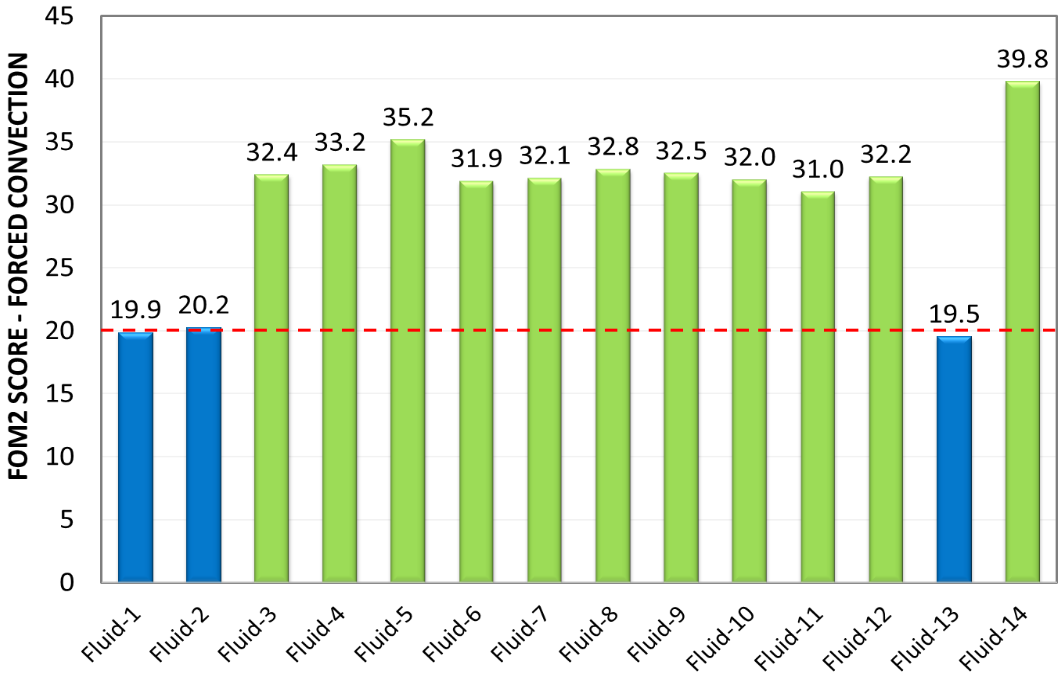


Figure 6: Figure of Merit (FOM2) for Forced Convection for Single Phase Immersion Liquids

Note that FOM2 for fluorochemical liquids is lower. However, actual testing of thermal performance shows that fluorochemical liquids have better thermal performance when heatsinks designed for air cooling are used for immersion. This seems to indicate that FOM1 is a better indicator of thermal performance of the liquid. In the discussion of FOM1, it was stated that optimum heatsink can be different for different immersion liquids. Highly viscous hydrocarbon liquids have difficulty going through the heatsink and therefore, there is not much flow that develops through the heatsink. FOM2 assumes the same flow condition for all liquid types. Lower viscosity liquids allow for heatsinks with higher fin density to be used and it increases the area available for heat dissipation. Higher viscosity liquids will utilize less dense fins and heat dissipation area is reduced.

Given the reasoning provided above, it is not intended to screen out any liquid based on FOM2 value. The specification for FOM2 is set at >19.

FOM2 = Figure of merit for forced convection for single phase immersion liquids > 19

Note that FOM2 is currently evaluated using properties at 25 °C. The reference temperature for evaluating FOM1 will be changed to 50 °C to reflect a temperature closer to actual use temperature. The only reason for choosing 25 °C for this initial release is that data for most liquids is available at 25 °C. However, liquid vendors should provide the data at 25 °C, 30 °C, 40 °C, 50 °C, 60 °C and 70 °C. Once liquid vendors start providing property data as a function of temperature covering the above stated temperature values, it will be easier to move the reference temperature to 50 °C along with a different spec value.

5.4 FOM3 – Viscosity for Pressure Drop

Pumps used in forced convection systems have to overcome pressure drop to push liquid through the IT equipment. Our goal is to figure out what fluid properties are critical for determining pressure drop. Therefore, a simple case of laminar flow through circular pipes is considered and pressure drop is given by:

$$\Delta P = f\,\frac{\rho V^2}{2}\frac{L}{D}$$

Where, f is the friction factor and is

$$f = \frac{64}{Re}$$

Therefore, pressure drop can be written as:

$$\Delta P = \frac{64\,\mu}{\rho V D}\;\frac{\rho V^2}{2}\frac{L}{D}$$

where:

- ρ: liquid density, kg/m^3
- μ: Dynamic viscosity of the liquid, $N\text{-}s/m^2$
- D: Diameter of the pipe, m
- L: length of the pipe, m
- V: Average velocity of liquid through the pipe, m/s

Since we want to identify fluid properties that determine pressure drop, we can drop any dimensional parameters such as (D, L) and fluid velocity (V) from the equation. This leaves dynamic viscosity of the liquid as the primary property that determines pressure drop. Lower viscosity liquids will flow easily through the IT equipment.

$$\Delta P = \frac{64\,\mu}{\rho V D}\;\frac{\rho V^2}{2}\frac{L}{D} \sim \mu$$

Figure 7 shows viscosity of immersion liquids. For immersion fluid spec, a target value of 1.5×10^{-2} N-s/m^2 is chosen. This value aligns with a single phase immersion liquid which is capable of cooling the 3rd generation of Xeon CPUs. Fluids with value lower than 1.5×10^{-2} N-s/m^2 are expected to have lower pressure drop and hence better thermal performance as they can flow easily through the IT equipment. As mentioned earlier in the document, optimized heatsink design for lower viscosity liquids is expected to have more fin density as compared to that for higher viscosity liquid. Under optimized design conditions, lower viscosity liquids can take advantage of higher heat dissipation area. Any additives that can lower viscosity should be considered for thermal performance. Lower viscosity liquids are preferred from thermal performance standpoint as they allow for higher fin density in heatsink design. Note that the viscosity specification must be met over the lifetime of the liquid. Note that pumping power for a typical immersion tank is a small fraction of the overall power usage. Need for lower viscosity liquid is more about the ability of the fluid to pass through the heatsink to deliver better cooling.

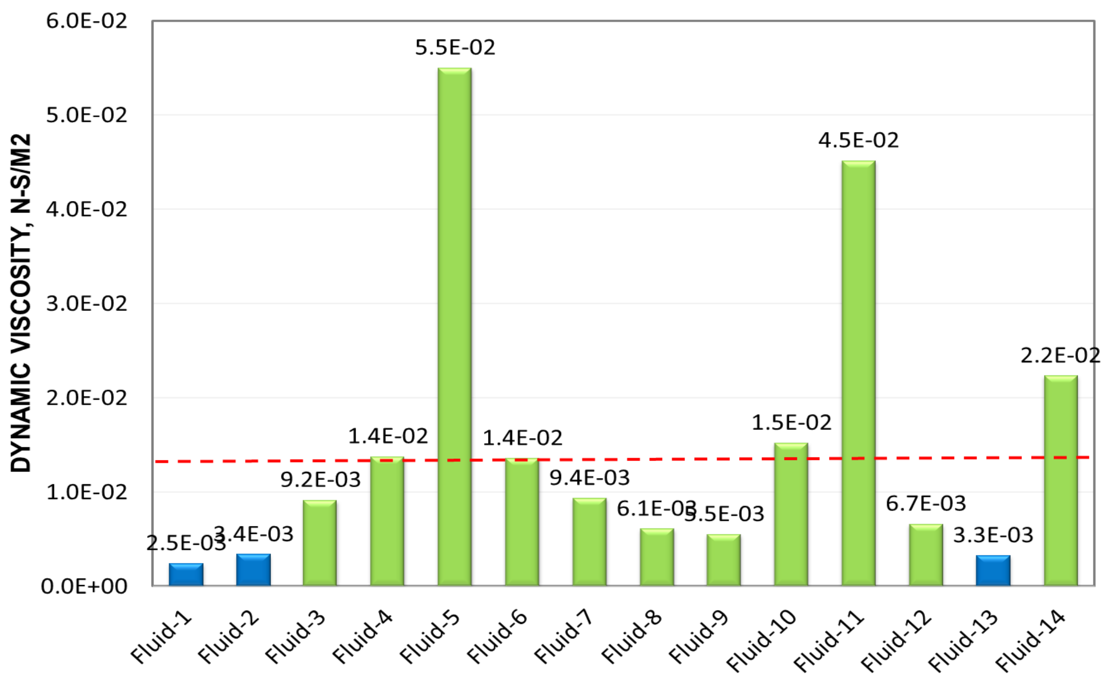


Figure 7: Dynamic Viscosity of Immersion Liquids

Note that the above formula assumes horizontal pipes. As it is noted in the next section, density is an important consideration for weight of the tank and is specified separately. In the current revision of the specification, reference temperature of 25 °C is used for dynamic viscosity. However, the liquid vendors should report data at 25 °C, 30 °C, 40 °C, 50 °C, 60 °C and 70 °C. Future revision of the specification will use 50 °C reference temperature with a different spec'd value.

Viscosity at low temperature is also of importance for pumping of coolant. Pump specification along with viscosity at a lower temperature value should be considered together to ensure that pump can still work with higher viscosity of the liquid. A low temperature limit of 0 °C is recommended to evaluate that pump is still capable of pumping the coolant to the immersion system. The value of 0 °C aligns with the minimum Tcase specification for Xeon CPUs.

There might be other use cases to consider where the viscosity of the liquid is important. An example of this may be the serviceability of the IT equipment, where the viscosity may play a role in the time the IT equipment needs to drip before servicing it. Lower viscosity liquids may reduce the drip time, while higher viscosity liquids may increase the time. There might also be other parameters to consider for serviceability, and it is currently outside of the scope of this specification.

5.5 Density

Immersion tanks with liquid filled can get quite heavy and the datacenter floor needs to be designed to handle the weight of the tanks. Based on the liquid density, the weight of the tank is going to change accordingly. Tank design should minimize the use of liquid to keep the fluid cost as well as weight to minimum. Figure 8 shows the density of many immersion fluids. Density specification is set to not exceed 2000 kg/m^3. This way it does not exclude any liquid based on density criteria, but sets a criteria for datacenter floor loading requirement to handle immersion systems with filled liquid that can have density up to 2000 kg/m^3. Reference temperature for density is 25 °C.

Pump power is another reason to specify density. Coolant is pumped at the bottom of the tank and it has to work against the height of the liquid in the tank. This brings in density as an important parameter.

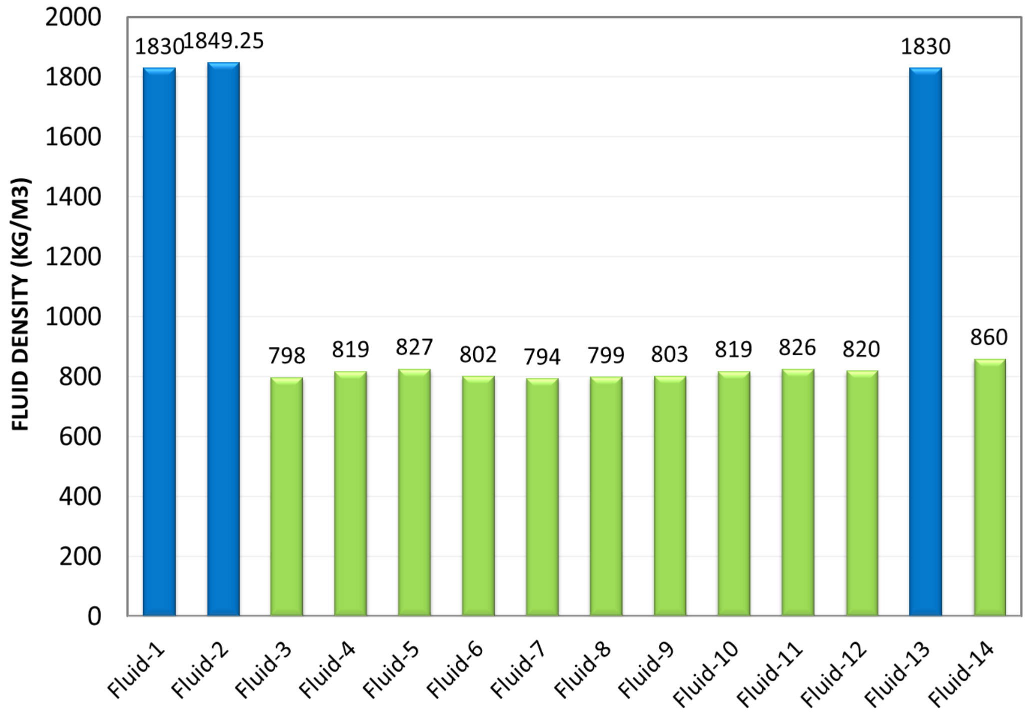


Figure 8: Density of Common Immersion Liquids

5.6 FOM4: Pool Boiling for Two-Phase Immersion

For pooling boiling heat transfer, the nucleate boiling regime is limited by the critical heat flux (CHF) above which it transitions to the film boiling regime, which can lead to overheating. The CHF relation was derived by Zuber et al.[18]:

$$CHF = \frac{\pi}{24}\sqrt{\rho_g}\, h_{fg}[\sigma g\,(\rho_f - \rho_g)]^{0.25}$$

where

ρ_g = vapor density [kg/m^3]
ρ_f = liquid density [kg/m^3]
h_{fg} = heat of vaporization [J/kg]
σ = surface tension [N/m]
g = gravitational constant [m/s^2]

Leveraging the above correlation, the Figure of Merit for 2-phase immersion cooling can be defined as[19]:

FOM for 2-phase immersion cooling (FOM4) = $\sqrt{\rho_g}\, h_{fg}[\sigma g\,(\rho_f - \rho_g)]^{0.25}$

In Figure 9, the above figure of merit is evaluated for four available two-phase fluids in the market. As shown, there is no significant difference in FOM scores for those fluids of four different boiling temperatures. In the figure, a target value of 1.1 x 10^6 is chosen. Note that all material properties are evaluated at the boiling temperature. Given that thermal performance of most two-phase liquids is going to be close, the boiling point of the liquid along with material compatibility and reliability of IT equipment in the liquid will drive liquid selection.

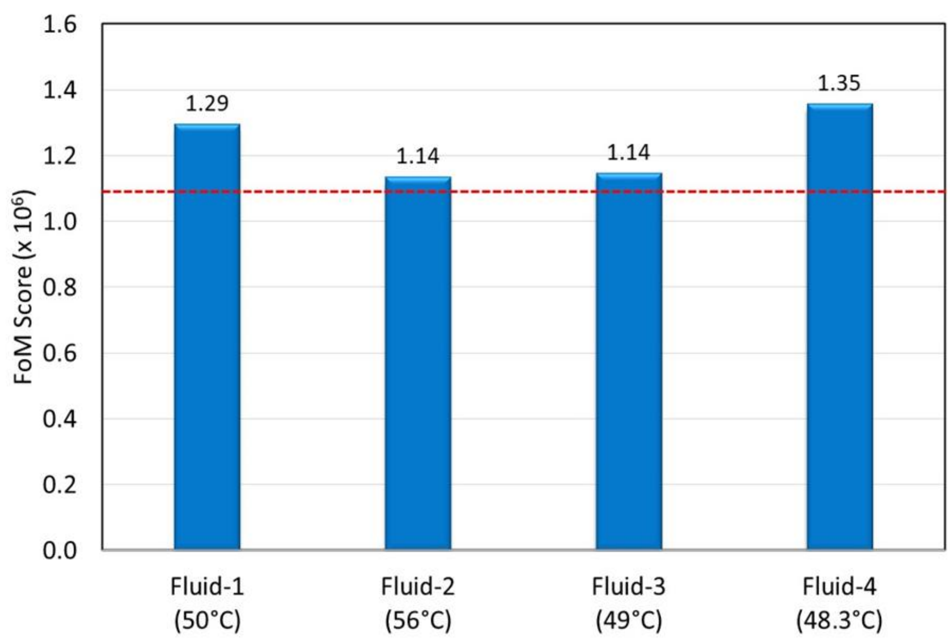


Figure 9: FOM4 Representing Pool Boiling Effectiveness for Two-Phase Immersion Liquids

It should be noted that the following properties, which are part of FOM1, FOM2 and FOM3, are not individually specified. These values should be reported by the liquid vendor at 25 °C, 30 °C, 40 °C, 50 °C, 60 °C and 70 °C using the ASTM standards mentioned in the table below.

Parameter	Units	Standard	Spec Value (1P)	Spec Value (2P)
Properties Captured in FOM				
Heat of Vaporization	J/kg	ASTM E2071		
Coeff. Of Expansion	K^{-1}	ASTM D1903		
Specific Heat	J/kg-K	ASTM E1269		
Thermal Conductivity	W/m-K	ASTM D7896		
Surface Tension	N/m	ASTM D1331		

5.7 Boiling Point Requirement for Immersion Liquids

Boiling Point Requirement for Single Phase Liquids

Most server CPUs and GPUs have some mechanism to throttle frequency and voltage to reduce power to keep temperature within specification. This throttling mechanism happens at temperatures typically no higher than 105 °C to 110 °C. If for any unforeseen reasons temperature continues to climb and the CPUs shut down at about 120-125 °C. Therefore, the temperature of liquid is not expected to exceed 125 °C. Therefore, a boiling point specification of 150 °C or greater, based on ASTM D2887, is recommended for single phase immersion liquids. However, not all the data centers are located at sea level. Immersion liquids will boil at a lower temperature for datacenters at higher altitude. For datacenters at higher altitude, it is still required that the liquid does not boil at temperature less than 150 °C. Therefore, sea level specification for boiling temperature is set at 155 °C which has 5 °C guardband built in for higher altitude (1500m). Note that there can be low power bare die components that do not need a heatsink. Therefore, this boiling temperature requirement is not reduced for lower heatsink surface temperature.

The same temperature spec of 155 °C or greater is recommended for flash point (ASTM D93 Closed cup) and critical temperature.

For end usage near sea level (altitude = 0m), boiling point and flash point requirement can be lowered to 150 °C.

Auto-Ignition Temperature

While the flash point is the ambient temperature at which the chemical can spark or ignite (if it meets an ignition source), the auto-ignition temperature is the lowest ambient temperature at which the chemical will spontaneously combust (*without* an ignition source)[20] [21]. The Auto-ignition temperature limit is defined by IEC 62368-1 (currently at 300 °C in the 3rd edition) The IEC 62368-1 safety standard is commonly adopted globally and used by regulators with respect to legal market access requirements. In general, globally, products require to be in compliance with IEC 62368-1 to legally be sold into the marketplace.

Educational note - As of October 2022 the OCP established an official liaison with TC108 Hazard Base Development Safety Team (HBSDT), the committee responsible for the IEC 62368-1 safety standard. The OCP's intention with this liaison is to meet with the TC108 HBSDT to look at opportunities of lowering the Auto-ignition limit.

Boiling Point Requirement for Two Phase Liquids

Boiling point between 45 and 55 °C is required for two phase liquids to meet cooling requirements of the IT equipment. A high boiling point leaves a smaller thermal budget to cool IT equipment with lower junction temperature limits. For example, memory requires 85 °C or below for 1x refresh for better performance. Many GPUs use high bandwidth memory (HBM) that also requires 85 °C or below junction temperature limit for 1x refresh for higher performance. Many high frequency CPUs can require lower temperature as well. Therefore, going above 55 °C for boiling point is not recommended for 2-phase liquids. Going below 45 °C poses other challenges, such as increasing power and water consumption required for cooling. If boiling temperature is too low, one can boil liquid at room temperature during summer months even when IT equipment is not powered.

5.8 Pour Point

It is expected that the immersion liquid does not freeze and is able to flow under gravity for any outdoor edge server. Freezing of immersion liquid can make it detached from the motherboard and cooling solutions. Therefore, a pour point of -30 °C or less is recommended to accommodate outdoor edge server applications in cold environments.

5.9 Vapor Pressure Requirement for Immersion Liquids

Vapor pressure is an indication of the evaporation rate of the liquid. The higher the vapor pressure the easier the liquid evaporates and can be referred to as volatile. A low vapor pressure is preferred to ensure no excessive amount of liquid evaporates and therefore needs to be replenished in the immersion application. Special containment and venting requirements might also be relaxed for a liquid with low vapor pressure.

Vapor Pressure Requirement for Single Phase Liquids

As an initial specification, a value of <0.8 kPa for low vapor pressure for single phase liquids is proposed. This is evaluated at 25 °C. For single phase liquids, the vapor pressure should be reported at 25 °C, 30 °C, 40 °C, 50 °C, 60 °C, and 70 °C. Future specification with a different value will reference 50 °C to reflect a temperature closer to end use condition. Using vapor pressure value at 50 °C will also be more reflective of how much liquid one is likely to lose due to evaporation. The value of 0.8 kPa can be met by many hydrocarbon and fluorocarbon based liquids.

Vapor Pressure Requirement for Two Phase Liquids

The target boiling point is between 45 °C and 55 °C for two phase liquids. This essentially means that vapor pressure equals 101.325 kPa (= 1 atm) at the boiling point. Vapor pressure requirement for two phase liquids is going to be much higher than those for single phase immersion liquids at room temperature. For this reason, care must be taken to ensure low vapor losses to the environment.

5.10 Total Acid Number (Guidance)

An increase in the total acid number (TAN) can indicate that a fluid is starting to break down into acidic compounds. These acidic compounds may negatively impact the dielectric properties of the fluid, accelerate the corrosion of components, and affect the thermal properties of the fluid. Therefore, it is important to minimize an increase in TAN to ensure reliable performance over product lifetime. Open Compute Project Immersion Requirements[22] lists unused minimum fluid requirements for acidity of several different fluid chemistries as below. As guidance, we suggest the acid number should not exceed 2x above the unused fluid limit. In the case of device failure, TAN of the fluid near the time of failure should be reported to the IT vendor for future spec development.

Acidity	Unused minimum Fluid requirement (mg KOH/g)[1]	Guidance for Lifetime minimum Fluid requirement (mg KOH/g)
hydrocarbons	≤0.01	≤0.02
natural esters	≤0.06	≤0.12
synthetic esters	≤0.03	≤0.06
fluorocarbons	≤0.001	≤0.002

5.11 Water Solubility

Water content in immersion fluids can impact dielectric properties and chemical stability. Assuming engineering controls are not implemented in the use case, the immersion fluid will continue to saturate with water until the solubility limit is reached. Therefore, the fluid's dielectric strength, dielectric constant, and loss tangent should be measured at the water solubility limit. If any of these parameters are out of spec or if water is known to affect the immersion fluid's chemical stability, the fluid supplier will provide the end user with a water content limit and a maintenance plan for monitoring and minimizing water content. Additionally, in the case of an unexpected device failure, water content of the fluid near the time of failure should be reported to the IT vendor, tank vendor, and fluid supplier.

5.12 Electrical and Signal Integrity Requirements

The Signal Integrity (SI) requirements on the immersion cooling liquid are from 20 MHz to 40 GHz, dielectric constant Dk (Er) should be less than 2.3 and dielectric loss tangent DF (tan δ) should be less than 0.05 across the entire frequency range to meet liquids exposed interconnect (i.e., socket, connector, PCB traces microstrip and cable) impedance requirements for High-speed I/O, such as Ethernet, PCIe and DDR interfaces.

Electrical and signal integrity parameters listed below must be met over the lifetime of liquid usage.

Dielectric Strength over lifetime	>6 kV/mm
Dielectric Constant (Er, Dk) from 20MHz to 40GHz*	≤2.3
Dielectric Loss Tangent (Df, tan δ) from 20 MHz to 40 GHz**	≤0.05
Volume Resistivity	> $1x10^{11}$ ohm-cm

* 1. With the current fluid dielectric properties measurement method, we can measure Er and loss tangent from 20 MHz to 40 GHz.

2. The best-known industry method so far to measure fluids with small Er in broadband frequency range is Keysight N1501A Dielectric Probe Kit and N1500A materials measurement software suite.
3. Measurement temperatures are from 20 °C to 70 °C, in 10 °C increments.

**4. Loss tangent (Df) is informative; For high speed I/O PCIe 5.0 and 6.0, for ethernet HSIO speed faster than 28G NRZ and 56G PAM4, liquid loss tangent requirement is less than 0.05.

No specification has been given regarding the refractive index of the liquid. The reasoning is that when the liquid is being used in the immersion application, contaminants in the liquid from the wetted materials may obstruct the signal path which creates a loss at the mated optical interface. In two-phase immersion, not only the contaminants are potentially challenging, but also there is the impairment on refraction due to the gas phase of the immersion liquid. This specification is therefore refraining from specifying a refractive index and relying on that closed optical connectors will be used in immersion applications, unless the impairments of contaminants and gas phase are well understood and contained.

Figure 10 below gives dielectric strength data for many common immersion liquids.

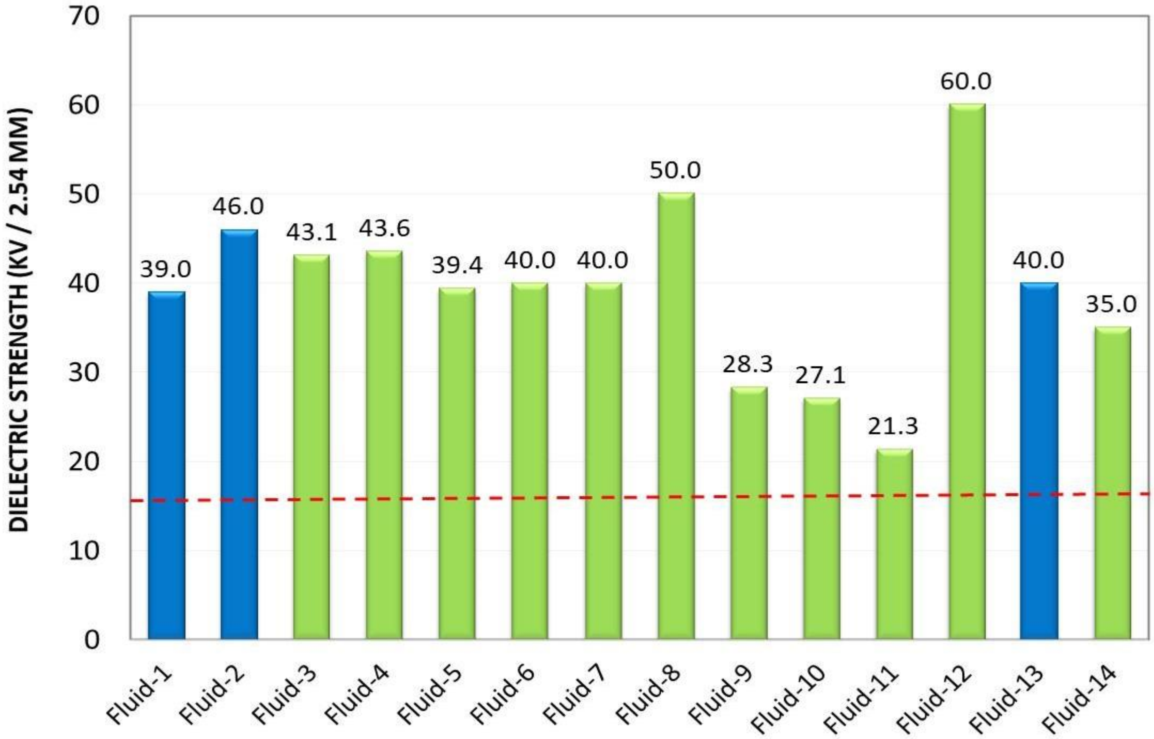


Figure 10: Dielectric strength data of immersion liquids (Unit: kV/0.1-inch gap, or kV/2.54 mm). Dotted line corresponds to 6 kV/mm.

Dielectric Strength is affected by water content, contamination, and temperature, generally inversely with moisture/water content and temperature. Recommend Dielectric Strength fluids spec to be > 6kV/mm for lifetime of the fluids. The units kV/mm are used to align with OCP recommended units for dielectric strength.

5.13 Dielectric constant Er (Dk) data

The dielectric constant (Er) of liquids is a function of both temperature and frequency. When frequency increases, the currently measured data shows no big change from 20GHz to 40GHz. When temperature increases, for example FC40, Er increases by about 0.1 to 0.2 from 25 °C to 50 °C. For single-phase fluids, the temperature range for measurements is from 20 °C to 70 °C in 10 °C increments. For two-phase fluids, the measurement temperature range is from 20 °C to boiling temperature minus 5 °C.

Dielectric constant (Er) of many commonly used immersion fluids is plotted in Figure 11. Dielectric constant (Er) should be less than 2.3. High dielectric constant can negatively impact high speed IO margin. Please refer to Figure 13 for PCIe 5.0 margin for different values of dielectric constant.

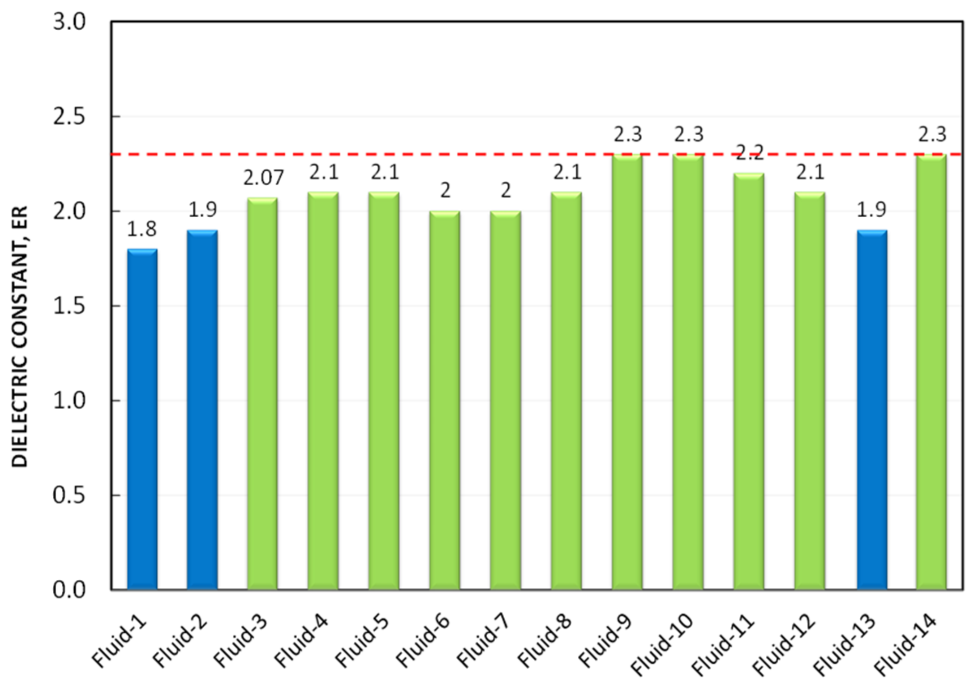


Figure 11: Dielectric constant Er (Dk) data of immersion liquids. The lower Er the better to SI. Dotted line corresponds to 2.3.

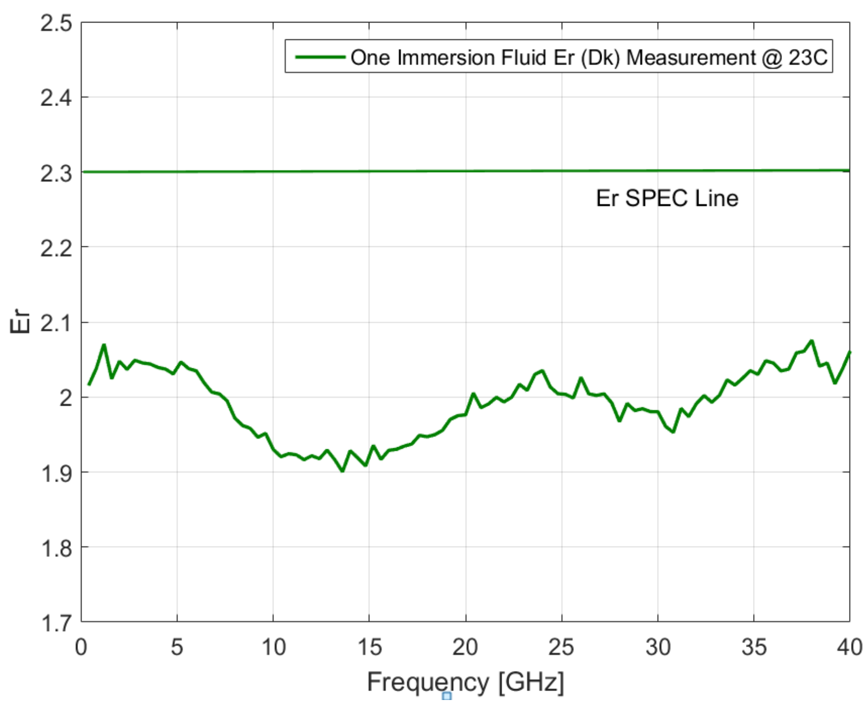


Figure 12: Fluid dielectric constant Er (Dk) measurement and requirement.

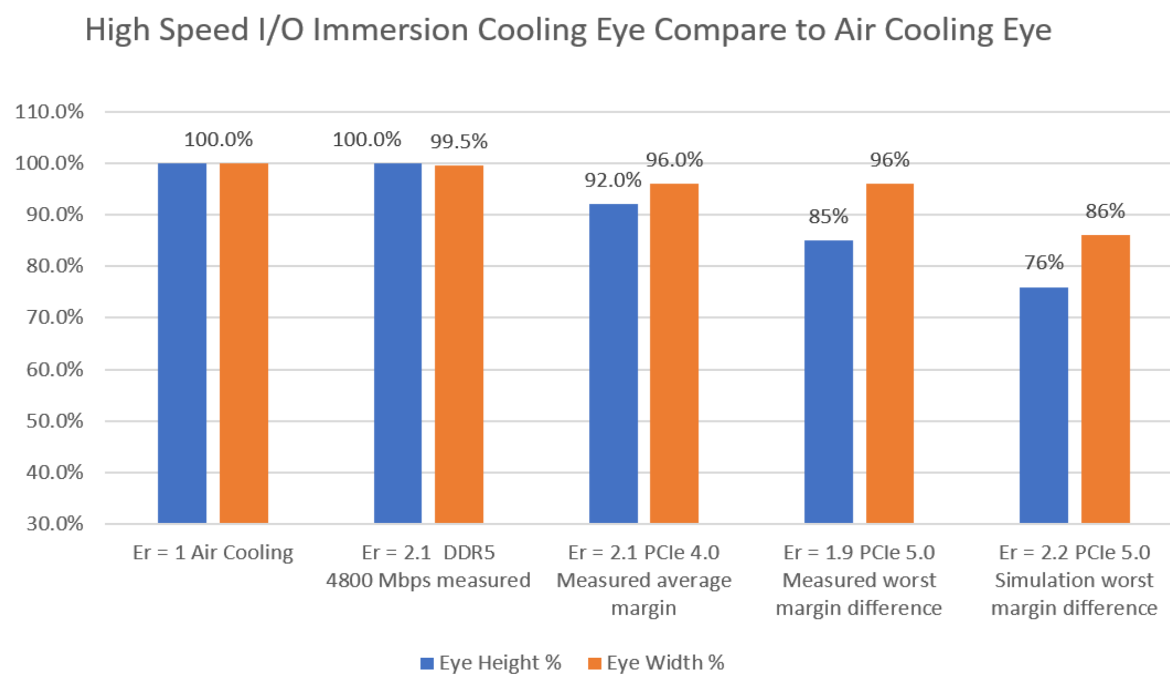


Figure 13: Fluid dielectric constant Er (Dk) impact to high speed I/O signal integrity Eye.

Figure 13 shows the relationship between fluid dielectric constant Er impact to high speed I/O eye height and eye width. When Er = 2.2, PCIe 5.0 32 Gbps eye starts to significantly degrade compared to the air cooling eye of the same bus.

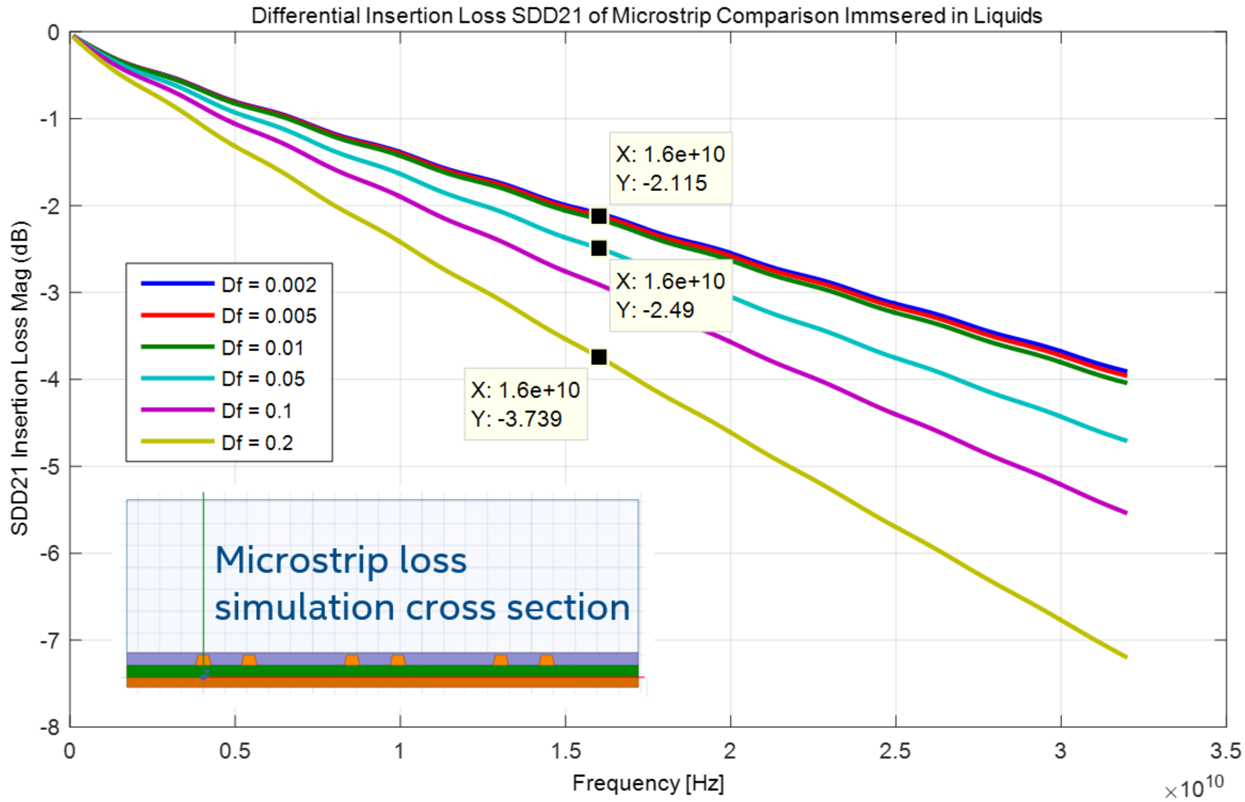


Figure 14: Fluid dielectric loss tangent (Df) impact on differential insertion loss at 8 GHz and 16 GHz for 1 inch long microstrip

Figure 14 is an immersed microstrip loss simulation of 1 inch long differential insertion loss SDD21 @8GHz, and the data show much more loss from Df (Loss tangent 0.1 and 0.2) compared to Df=0.05 and less. With loss tangent Df=0.1, 1" long Microstrip, there is 0.4 dB more loss compared with Df=0.05. For PCIe 5.0 (16 GHz), typical microstrip insertion loss is 2.1 dB / inch, 0.4 dB difference is 19%. It is considered too high, so Loss tangent target is set to be 0.05.

Loss Tangent Df	**Loss @ 8GHz, Unit: dB / inch**	**Loss @ 16GHz Unit: dB / inch**
Typical Microstrip	1.2 dB	2.1 dB
Df = 0.005	1.2 dB	2.1 dB
Df = 0.01	1.2 dB	2.1 dB
Df = 0.05	1.38 dB	2.49 dB
Df = 0.1	1.58 dB	2.9 dB
Df = 0.2	2.0 dB	3.74 dB

Liquids Df has more impact on the connector. Figure 15 and table shows QSFP DD connector loss comparisons for the liquids with 0.05 Df and 0.2 Df. The extra loss with Df=0.2 is 6.87 dB @ 26.6 GHz (112G PAM4 signal) which equals 46 inches long ethernet cable loss.

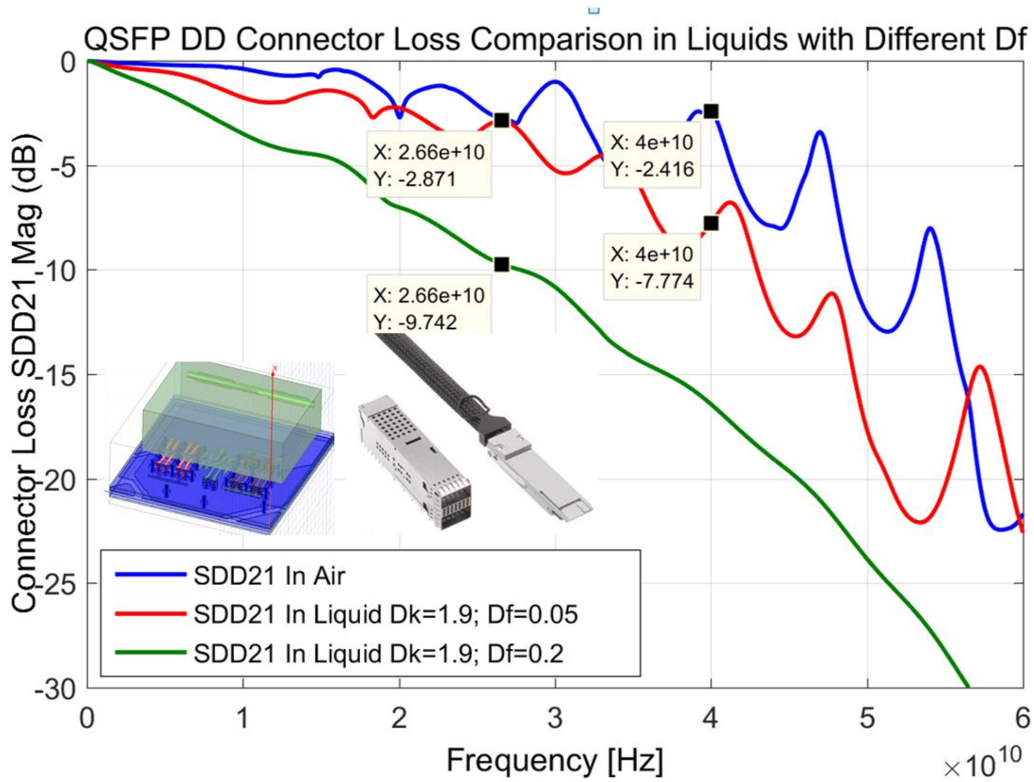


Figure 15: Illustration of fluid dielectric loss tangent (Df) impact on QSFP Ethernet connector insertion loss.

Liquid Loss Tangent Df	**Loss @ 26.6 GHz (112G PAM4)**	**Loss @ 40 GHz (112G to 200G PAM4)**
In Air	0.43 dB	2.4 dB
Df = 0.05	2.87 dB	7.77 dB
Df = 0.2	9.74 dB	16.44 dB
A typical AWG27 Ethernet cable	0.15 dB / inch	0.2 dB / inch
shorter ethernet cable length support compares Df=0.05 with Df=0.2	-46 inch (1.2 m) (9.74-2.87)/0.15=46 inch	-43 inch (1.1 m) (16.44-7.77)/0.2=43 inch

6. Safety, Environmental and Chemistry requirements

Immersion fluids must be evaluated for their safety and environmental impact. Immersion cooling should strive for low persistence, toxicity, and bioaccumulation characteristics. Below, we summarize the broad categories to be considered. These criteria should be considered throughout the life cycle of the immersion fluid i.e., manufacturing, use, and recycling/disposal/disposition of the fluid. These criteria must be evaluated for each fluid independently by experts. Additional validation testing may be required.

Environmental and Human health impacts:

- Acute and chronic toxicity (T) for humans, plants, and animals
- Persistence (P) and bioaccumulation (B)
- Atmospheric Impacts (Ozone depletion and Global Warming Potential)
- Persistence, breakdown mechanisms and pathways (in air, water, and soil)
- Toxicity of subsequent breakdown products to the atmosphere

6.1 Toxicity

Fluid properties should minimize any potential harm to both Human Health (HH) and environment. Adverse human health impacts from any chemical can be diverse, including oral/dermal/inhaled toxicity, eye irritation, organ toxicity, reproductive toxicity, and carcinogenicity, all of which must be carefully evaluated.

Ecological Toxicity includes persistence in the environment, bioaccumulation(B) in the food chain, aquatic toxicity, and terrestrial toxicity and addresses the potential harm to the ecology.

- **Persistence:** Persistence refers to ease of degradation of a chemical. The mechanism of degradation (photolytic, chemical, etc.) also needs to be considered to evaluate the risks associated with escapes ranging from minor to significant.

- **Bioaccumulation:** Bioaccumulation refers to the process and rate of accumulation of a chemical in an organism or an entire ecology. Most fat-soluble substances tend to bioaccumulate, so this preferential solubility needs to be given careful consideration while evaluating immersion fluids.

- **Aquatic toxicity**: The toxicity to aquatic organisms is measured in terms of LC50 (lethal concentration), EC50 (concentration to reduce growth) and NOEC (no-effect concentration). Chemicals with lower LC50/EC50/NOEC pose a higher toxicity risk to aquatic life and are not recommended.

- **Terrestrial toxicity:** Terrestrial toxicity is defined as the study of the effects of a chemical substance on terrestrial organisms. Terrestrial toxicity may be monitored by measuring the lethal dose concentration (LD50) and no-effect concentration (NOEC) for earth worms (OECD 207), soil-microbes (OECD 217), plants (OECD 227) and bees (OECD 213). Under EU REACH, information on terrestrial toxicity is required for chemicals produced or imported in quantities > 100 tons/year if terrestrial exposure is likely. Under global pesticide regulations, terrestrial toxicity data is often mandatory (especially for new active substances).

- **Human Toxicity:** Immersion fluids of choice must have minimal to no impact on human health. Exposure to hazardous chemicals can result in both acute and chronic health impacts depending on the toxicity of the substance and the mode of exposure. Acute health effects include skin irritation/damage, eye irritation/damage and lethality. Chronic health impacts are a result of longer duration of exposure and include sensitization (skin and respiratory), organ damage, and carcinogenicity. National Institute of Occupational Health and Safety (NIOSH) provides control bands for all chemicals ranging from A to E, with E being the most toxic. The NIOSH control band of a chemical is usually provided in a safety data sheet (SDS) and must be considered along with Occupation Exposure Limit (OEL) to determine safety at workplace where human exposure is possible. Acute inhalation toxicity as categorized by the Globally Harmonized System of Classification (GHS) Classification Criteria for Acute Toxicity.

- **Carcinogenicity:** Immersion fluids chosen must have no known carcinogens. Carcinogenicity for several chemicals is listed in OSHA standards 1910, 1915 and 1926. Carcinogenicity of pure chemicals is detected using AMES assay and in-vitro chromosomal aberrations tests. For single phase hydrocarbon based immersion fluids, where additives are added to enhance properties, the following guidelines provided by International Agency for Cancer Research (IARC), National Toxicology Program (NTP) and American Conference of Governmental Industrial Hygienists (ACGIH) must be followed.
    1. No ingredient of this fluid present at levels greater than or equal to 0.1% is identified as probable, possible, or confirmed human carcinogen by IARC.
    2. No ingredient of this fluid present at levels greater than or equal to 0.1% is identified as a known or anticipated carcinogen by NTP.
    3. No ingredient of this fluid present at levels greater than or equal to 0.1% is identified as a carcinogen or potential carcinogen by ACGIH.

6.2 Atmospheric Impacts (ODP and GWP)

GWP is a measure of the relative global warming potential of different gases. It assigns a value to the amount of heat trapped by a certain mass of a gas relative to the amount of heat trapped by a similar mass of carbon dioxide over a specific period of time. The Intergovernmental Panel on Climate Change (IPCC) chose carbon dioxide as the reference gas and its GWP is taken as 1. The higher the GWP value, the more that gas warms the Earth compared to carbon dioxide. GWP values for hydrofluorocarbons (HFCs) can range from less than 1 to over 10,000.

Similarly, ODP (Ozone Depletion Potential) is a measure of the capacity of a compound to destroy stratospheric ozone, which protects the earth from harmful high energy ultraviolet radiation. The Montreal Protocol governs the phase-out of ozone depleting substances, and is the reason that chlorofluorocarbons (CFCs) are no longer used in refrigeration systems, having been replaced by hydrofluorocarbons (HFCs). The Kigali amendment to the Montreal Protocol further restricts the use of certain HFCs because of their high GWP.

For any immersion fluid, the ODP shall be zero. The GWP shall be low, bearing in mind that any immersion deployment has several sources of climate impact that must be considered holistically, and that fluid choice is only one of them.

6.3 PFAS Regulatory Risk

Per – and Polyfluoroalkyl Substances (PFAS) are defined as any substance that contains a -CF2- or -CF3 group within its molecular structure. Many developing regulatory restrictions on the PFAS class of chemistries adds risk to some fluid choices.

For all immersion applications, fluid manufacturers and users should become familiar with the efforts by the EU and multiple US States that intend to significantly restrict the use of PFAS, particularly for non-essential uses. It remains to be seen which criteria will be used for regulation and what will constitute essential use. Following are notes of awareness.

i. Within the EU, the country of Netherlands is working with the countries of Denmark, Germany, Norway, and Sweden to develop a dossier that contains a restriction proposal that will ban all uses that are not deemed to be essential. The dossier is expected to be published in Q1’23, and to be followed by a 6-month public comment period to allow for submission of comments and technical information that may be useful for determination of essentiality. It is believed that a derogation will be required for any use to be allowed past the expected effective date of the restriction/ban in 2026. For more information, please see[23]: https://www.rivm.nl/en/pfas/restriction-proposal-pfas/qas-pfas-restriction-proposal
ii. Within the US, multiple States have initiated efforts intended to restrict all non-essential uses of PFAS. In July 2021, the State of Maine passed a law that intends, by 2030, to prohibit the sale of PFAS in any product that is not specifically designated as a currently unavoidable use by the Maine Department of Environmental Protection. The Department is aware that many existing refrigerants either meet or contain a chemical that meets the definition of a PFAS under this program and that future refrigerants may similarly meet the definition. Closer to 2030 the Department may undertake an investigation to determine if refrigerants are, at that time, a currently unavoidable use. For more information, please see[24]: https://www1.maine.gov/dep/spills/topics/pfas/PFAS-products/index.html

6.4 Additional Chemistry Requirements

The following chemistry requirements ensure that the immersion fluid chosen is chemically compatible and suitable for use in an immersion environment.

- **Color Requirements:** Immersion fluid should be less than or equal to a 1 on the ASTM D1500 standard at beginning of life and the fluid should be monitored for significant color changes during the service lifetime. There are many different mechanisms that can cause changes to fluid color, some that can indicate a degradation in fluid properties and others that are purely aesthetic. Some fluid degradation modes include but are not limited to: UV exposure by sunlight or fluorescent lighting, oxidation, byproduct formation, pigment/contaminate leaching, and radical inhibitor attenuation. Each fluid chemistry will have unique risks associated with color change, please consult fluid supplier about any significant changes in color or opacity. It is recommended that if there is a change of color of more than +2 units using ASTM D1500 or if there is significant color change and the color change is not enveloped by ASTM D1500 when compared to the original fluid, a fluid analysis panel should be carried out with specific testing designated by the fluid supplier to assess fluid properties and degradation. If a fluid property falls outside of the lifetime spec values discussed in this document, the end user should consider replacing the fluid.

- **Durability:** Fluid should meet the fluid property specifications and requirements under operating conditions for 10 years.

- **Oxidation Potential:** Oxidation is a cause of concern in single phase immersion fluids and is responsible for viscosity increase, darkening, foul odor, sludge and sediment formation, additive depletion, base oil breakdown, acid number (AN) increase, rust formation and corrosion. Immersion fluids must have low oxidative potential as determined by standard tests such as ASTM D4310 - the sludge and oxidation tests and FTIR analysis.

- **Odor Requirements:** Single phase fluids should have low odor at operating conditions of <60 °C for greater than or equal to 10 years. Low odor will be defined as having less relative odor than 200 ppb of n-butanol dissolved in water as determined by ASTM E544-18. Fluids should not contain or decompose into known odor causing volatile compounds above each compound's odor threshold under operating conditions of <60 °C for greater than or equal to 10 years. For two-phase fluids, the odor should be evaluated at the fluid’s operating temperature if safe to do so.

- **Chemical Purity:** The immersion fluids considered must have ACS grade purity (>=95%) which is deemed suitable for use in laboratory and analytical applications. This standard is determined by American Chemical Society. Consideration should be given to purer chemicals devoid of sulfur, acidic impurities, polychlorinated biphenyls etc. as these impurities raise the toxicity and corrosiveness of the chemical.

- **Safety Requirements:** Any immersion fluids and containers shall comply with insulating liquid requirements of IEC 62368-1 – Audio/video, information, and telecommunication technology equipment – Part 1: Safety Requirements. This is a safety standard that classifies energy sources, prescribes safeguards against those energy sources, and provides guidance on the application of, and requirements for, those safeguards.

- **Flammability:** Fluids should have lower flammability risk according to NFPA 704[25] Standard. This rating provides information on severity of each fluid along with vital information to emergency personnel regarding fire-fighting techniques and the appropriate personal protective equipment.

7. Final Summary Table of Fluid Specification

The table below summarizes all the requirements for single and two-phase immersion liquids.

Parameter	Units	Standard	Spec Value (1P)	Spec Value (2P)
Temperature Specs				
Boiling Point (eng liquids)	°C	ASTM D2887	> 155°C at 1 atm for 1500m altitude use, > 150°C at 1atm for sea level use	> 45°C, < 55°C at 1 atm
Pour Point	°C	ASTM D97	< -30°C	< -30°C
Closed Cup Flash Point (for oils)	°C	ASTM D93	> 155°C at 1 atm for 1500m altitude use, > 150°C at 1atm for sea level use	
Critical Temperature	°C		> 155°C	> 155°C
Auto Ignition Temerature	°C	IEC 62368-1	Refer to IEC 62368-1	Refer to IEC 62368-1
Pressure Specs				
Critical Pressure	MPa	ASTM D6378		
Vapor Pressure	kPa	ASTM D6378	< 0.8	N/A
Figures of Merit				
FOM1 (Natural Convection)[1]			> 45 (Tier2), >35 (Tier1)	N/A
FOM2 (Developing Laminar Flow)[1]			> 19	N/A
FOM3 (Dynamic Viscosity)[1]	$N\text{-}s/m^2$	ASTM D7042	< 0.015	< 0.015
Density[1]	kg/m^3	ASTM D4052	< 2000	< 2000
FOM4 (2P Immersion Fluid)[3]			N/A	> 1.1e6
Electrical Parameters				
Dielectric Strength over lifetime	kV	IEC 60156	> 6 kV/mm	> 6 kV/mm
Dielectric Constant (DK, Er) from 20MHz to 20GHz to 40GHz [2]			<=2.3	<=2.3
Dielectric Loss Tangent (Df, tan δ) from 20MHz to 20GHz to 40GHz [2]			<=0.05	<=0.05
Volume Resistivity	ohm-cm	ASTM D1169	> 1.0e11 ohm-cm	> 1.0e11 ohm-cm
Environmental Parameters				
Ozone Depletion Potential			0	0
Others				
Toxicity			Refer to section 5.1	Refer to section 5.1
Color		ASTM D1500	Refer to section 5.4	Refer to section 5.4
Odor		ASTM E544-18	Refer to section 5.4	Refer to section 5.4

Notes:

1. Evaluated at 25 °C. However, parameter values should also be reported at 25 °C, 30 °C, 40 °C, 50 °C, 60 °C and 70 °C. Future revisions will change the reference temperature to 50 °C with different sets of values.
2. This specification must be met over a temperature range from 20 °C to 70 °C.
3. Evaluated at the boiling temperature.
4. Total acid number and water solubility guidance limits are provided in the body of the text.
5. PFAS and GWP guidelines are provided in the body of the text.
6. An Excel tool[26] is available at the Open Compute Immersion Wiki[27] (https://www.opencompute.org/wiki/Cooling_Environments/Immersion) to compute FOM values based on user provided input values.

7.1 Other Considerations

Compatibility of liquids with CPU, GPU packages, IT equipment, tanks and CDU is critical in ensuring that the liquid can be used for immersion application. In addition, one must show that the IT equipment, tanks and CDUs can work reliably over their intended lifetime in the immersion liquids. Additional specifications will be added in future to cover both material compatibility and reliability requirements.

8. References

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