Design Guidelines for Immersion-Cooled IT Equipment

Revision 1.0

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Revision History

Revision	**Date**	**Comments**
1.00	Dec 03, 2020	Submitted to IC
1.01	Dec 07, 2020	Minor formatting correction

Executive Summary

Open Compute Project equipment that enlists immersion cooling may have some unique and specific requirements. The compute performance as well as the protection from overheating that is gained with immersion is generally worth the investment. Nearly all computing and communications equipment today is designed and manufactured for operation in air. Immersion cooling requires attention to several material and fluid handling specifications to ensure safe and reliable operation. This document provides Immersion guidelines and best practices from experts in thermal handling, fluid materials science and engineering, server integration, and power connectivity that OCP has brought together worldwide.

Abstract

The following topics are covered within this whitepaper:

Material Compatibility: Determining compatibility with immersion. Not all parts of the end-user supply chain will be tasked with ascertaining compatibility, i.e. CPU thermal interface material (TIM) is present between the chip die and the Integrated Heat Spreader (IHS) and is best researched and qualified by the original manufacturer. But a network extension cable can be practically validated and selected by a system integrator or end user. High level distinctions exist between the requirements for single-phase Hydrocarbons/Fluorocarbons and for two-phase Fluorocarbons.

Thermal Design: Changes in thermal behavior commonly result from immersion. When IT equipment is optimized for immersion, more benefit can be gained. This section describes the potential impact and extent of new possibilities when thermal behavior under immersion is considered in designing devices and equipment.

Mechanical Design: Certain fundamental changes can be expected when working with immersion technologies. Immersion rack enclosures are often quite different from traditional air racks. The shape, position and operation can be optimized to be different than air equipment. Vertical positioning of CPUs in an open bath immersion system and fully sealing an enclosed chassis are two examples. This results not only in a different IT design, but also in a different operating model (which is not fully covered in this white paper).

Electronic Design: Density and layout are covered, and new design considerations for electronics when designing for fluid. Signal integrity, network connectivity, CPUs, storage devices and more.

Software: BIOS, Firmware and IPMI features which should be implemented to allow effective operation within immersion solutions, without disqualifying the operation of the same equipment in air.

Required reading: OCP ACS Immersion requirements document:
https://www.opencompute.org/documents/ocp-acs-immersion-requirements-specification-1-pdf

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1. Introduction

This Open Compute Project (OCP) whitepaper is written for current and potential designers, manufacturers, integrators and end users of immersion-cooled OCP-ready equipment. OCP equipment that is air-designed can be retrofitted and supported as well, with the help of this reference guide. Integrators and component suppliers will find useful information specific to their preparation for immersion-cooled OCP systems.

The nature of immersion cooling requires attention to all components and materials that will come into contact with dielectric fluids. The OCP Immersion workstream discusses considerations for cooling with dielectric fluids and the layout of IT equipment to accommodate thermal optimization and fluid compatibility. Immersion systems are supported through enclosed chassis for vertical Open Rack or tank-style integration and can support single or two-phase fluid cooling types.

Immersing servers and information technology (IT) equipment in a dielectric fluid enables substantial energy savings and accommodates growing load densities. The existing proprietary immersion cooling solutions and numerous case studies have established the effectiveness and energy savings for new construction or a retrofit from the device to the facility level.

Immersion cooling of data center equipment promises to improve reliability and overall equipment life, with lower service and repair costs. Immersion cooling greatly reduces failures such as solder joint failures, oxidation and corrosion of electrical contacts, electrostatic discharge, and ambient particulate. It allows for much more consistent and controlled operating temperature and humidity. Bill of materials (BOM) component count and cost reductions are intrinsic to immersion too, as fans, conventional heat sinks, and operating environment controls such as humidity sensors are eliminated. These reliability advances include a reduction in corrosion and electrochemical migration, lessening of environmental contamination like dust, debris, and particulates, reduced thermal shock, and mitigation of tin and zinc whiskers. Furthermore, the improved thermal management of components due to the increased heat capacity of fluids, can provide a significant increase in compute performance.

2. Material Compatibility

The chemical and physical interactions between the dielectric fluid and various components introduce component lifecycle loads that differ from those observed in traditional air cooling and can result in degradation of material properties or component functionality. Understanding the mechanisms by which the hydrocarbon or fluorocarbon coolant and components interact, and mitigation options are important. The extent to which the coolant would be a contaminant vector is central to the study of reliability in immersion cooling.

This chapter suggests experiments for predicting degradation of cables, printed circuit boards, packages, optical fibers and passive components. Dielectric coolant health is typically assessed by measuring shifts in composition or thermophysical properties under conditions representative of the end-use application.

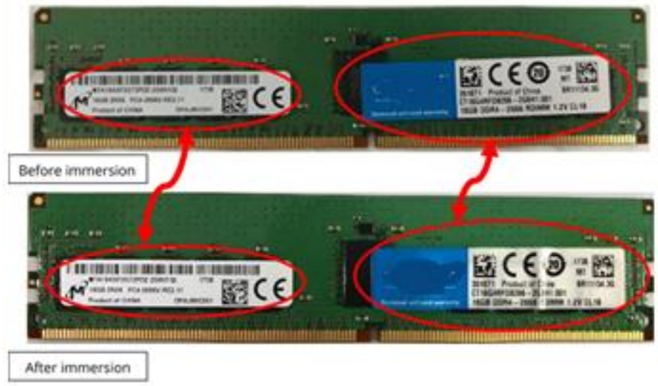
2.1 Components to Check for Compatibility & Material Source of Contaminant

In an air-cooled data center environment, air quality is monitored and maintained to mitigate damage to critical infrastructure including the reliability of ITE. According to ASHRAE the potential reliability issues derive from particulates and corrosive contaminants. The ASHRAE published white paper ‘2011 Gaseous and Particulate Contamination Guidelines for Data Centers’ recommends that data center air quality is monitored and cleaned according to ISO 14644-82. In the case of immersion-cooled systems, the electronics and supporting equipment themselves may act as a source of contaminants. In this sense, the designer has a control over contamination.

All materials need to be validated for implementation in immersion systems. The following tables outline common examples to take into consideration for such validation.

Figure 1- Potential issues and a mitigation plan in ITE immersion design: Examples of undoing stickers

Labels (stickers)



Potential issue	**Effect**	**Mitigation**
Dissolvable glue/Adhesives and inks for all fluids.	Information loss No recorded polluting effects.	Document sticker information, cover with coolant resistant tape (acrylic), use etched label.

Figure 2- Potential issues and a mitigation plan in ITE immersion design: Examples of EPDM swelling in capacitors

Capacitors

Potential issue	**Effect**	**Mitigation**
EPDM sealing may Interact with fluids.	Swelling of EPDM sealing and bending of terminal leads.	Use different capacitors which do not contain EPDM.

Figure 3- Potential issues and a mitigation plan in ITE immersion design

Connectors, sockets, peripherals or sealants

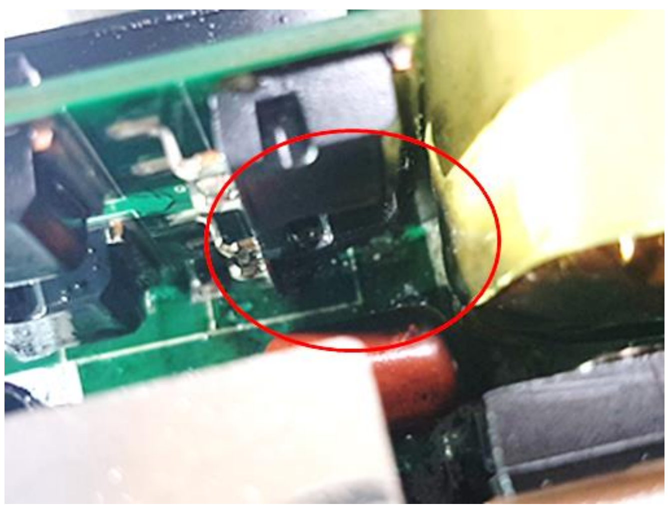
Potential issue	Effect	Mitigation
Materials may have fluid compatibility issues.	Functionality may be affected, voltage drop, disconnects.	Consider different material.

CMOS battery

Potential issue	Effect	Mitigation
Battery materials may have fluid compatibility issues.	Loss of CMOS information and/or system functions.	Ensure compatible batteries.

Figure 4- Potential issues and a mitigation plan in ITE immersion design: Example of exploded semiconductor due to failed relay

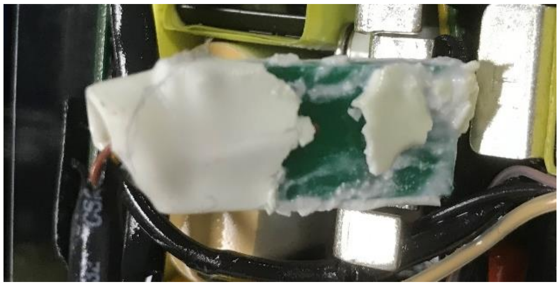
Relays (PSU)



Potential issue	Effect	Mitigation
Unsealed relays may be slowed down by fluid viscosity.	Loss of function of affected circuits or overloaded circuitry.	Select different PSU or use immersion compatible relays.

Figure 5- Potential issues and a mitigation plan in ITE immersion design: Example of disintegrated heat shrink

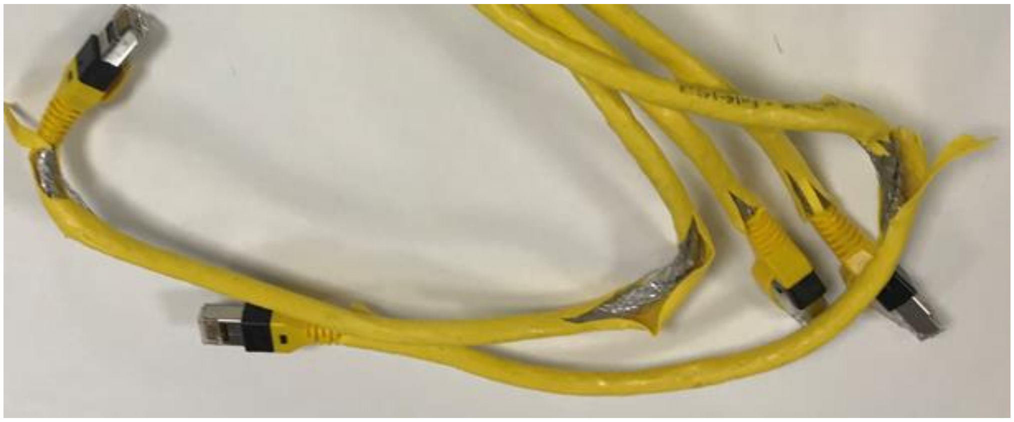
Heat shrink



Potential issue	Effect	Mitigation
May be intolerant to dielectric fluids, especially at higher temperatures (60°C+)	Materials may disintegrate/react with fluid. Pollution of dielectric fluid.	Replace with suitable materials.

Figure 6- Potential issues and a mitigation plan in ITE immersion design: Example of Stiffened and disintegrated wire jacket

Cables



Potential issue	Effect	Mitigation
Material compounds like plasticizers, chlorine, sulphur etc. in the jackets may dissolve into the dielectric fluid.	Materials may disintegrate/react with fluid. Pollution of dielectric fluid.	Use compatible cabling.

Figure 7- Potential issues and a mitigation plan in ITE immersion design

Thermal compounds and pastes		
Potential issue	**Effect**	**Mitigation**
May dissolve or be affected by immersion	Reduced thermal transfer capabilities of affected assembly. Pollution of the dielectric fluid	Replace with compatible TIM (e.g. Indium foil), remove TIM or remove sink/spreader.

Figure 8- Potential issues and a mitigation plan in ITE immersion design:

Heat sinks		
Potential issue	**Effect**	**Mitigation**
Air design heat sink may not be suitable for immersion	Component is not effectively cooled. Different thermal performance is expected.	Remove if not required; Ignore if component remains within required temperature limits; Replace with design optimized for immersion.
Mechanical HDD’s		
Potential issue	**Effect**	**Mitigation**
Fluid may penetrate through the air vent.	HDD malfunction due to penetrated fluid causing mechanical resistance to sensitive mechanical parts in HDD.	Use hermetically sealed helium or solid-state drives.

2.2 Material Compatibility: Single-Phase Immersion Cooling (Hydrocarbons)

Traditional material compatibility tests like ASTM D471 and D2240 can be performed. In such tests, a material is typically soaked in the fluid for a period of time, often at elevated temperature (above expected operating temperatures), and changes in properties such as hardness, durometer and volume are recorded and compared with the results of similar tests in air. Some of the proven methods are explained below:

Figure 9- Test conditions for material compatibility

Test # 1: General material compatibility	
Goal	**Evaluation method**
To understand material compatibility of servers under operation.	1. Visual Inspection/cosmetic changes of the samples from the immersed server; 2. Check the deposition of plasticizers, debris and contaminants on components and their effects on thermal performance; 3. Cross sectioning and optical microscopic images to analyze electronic packaging structures; 4. Thermal testing and analysis by tracking component temperature and performance over time; 5. Mechanical testing and analysis of structural components, such as socket, retention, clips, etc.; 6. Corrosion of electronic interconnects, solder materials and any exposed metallization including the chassis.

Test # 2: Thermal aging of solder, PCBs, PVCs, Optical Fibers, SFP or QSFP, and Passive Components	
Goal	**Evaluation method**
Experimental approach: Thermal aging/accelerated testing of immersed samples of PCBs, PVC jackets, passive components and optical fibers using an oven or environmental chamber.	
Understanding material compatibility of components.	1. Mechanical, Thermal, and Electrical testing of aged samples; 2. Structural analysis through Optical, X-ray tomography and SEM (scanning electron microscopy) analysis.

2.3 Material Compatibility: Single-Phase Immersion Cooling (Fluorochemicals)

Since most organic polymers used in the fabrication of modern electronics are hydrocarbons in nature, fluorochemical fluids have virtually no affinity or solvency for them. Clean fluorochemical fluids, therefore show excellent compatibility by traditional material compatibility tests like ASTM D471, D2240, etc. In real world immersion cooling applications, the fluorochemicals will become contaminated with hydrocarbons such as dioctyl phthalate (DOP) that is extracted from polyvinyl chloride (PVC) wire insulation or silicone oils extracted from silicone polymers, solder flux, or thermal interface materials, for instance. Because the fluorochemical has very little solvency for these hydrocarbon contaminants, it is easily saturated with them (perhaps at concentrations of only a few parts per million). This also means that the fluorochemicals readily give up these hydrocarbon contaminants to other materials that have an affinity for them. One may therefore observe swelling of a hydrocarbon polymer as it absorbs material extracted from another hydrocarbon polymer.

This is called a “secondary incompatibility” because the fluorochemical merely acts as a contaminant vector. Effects on the performance of either the source or sink of a contaminant are rare. For example, leaching out of plasticizers from CAT6 network cables will make the jacket stiffer but will not affect the functionality of the cable. In two-phase immersion, fluorochemical fluids can act as a vector in another way.

2.4 Material Compatibility for Two-Phase Immersion Cooling (Fluorochemical Fluids)

The boiling and condensation processes inherent to two-phase cooling have important implications for material compatibility and system health. During boiling, for example, the relatively non-volatile hydrocarbon contaminants dissolved in the fluid are deposited on boiling surfaces by distillation in much the same way that lime accumulates in a tea kettle with time. The vapor evolved by boiling the fluid, being freshly distilled, is free of hydrocarbon contaminants and once condensed, has a high affinity for them. If this condensate comes into contact with elastomers containing hydrocarbon contaminants, the fluid will extract or solvate these substances and upon returning to the boiling fluid, leave the oil behind.

This mechanism for transporting relatively non-volatile contaminants from one part of the system to another is unique to two-phase systems and forms the basis for Soxhlet extraction, a technique by which a fluid is used to extract mobile compounds from a solid phase. It is used, for example, to extract essential oils from plants, or lipids from food samples to assess fat content. This quick and inexpensive lab test for assessing material compatibility in both single and two-phase applications should be done as explained below.

2.5 The Soxhlet Extraction Material Compatibility Test

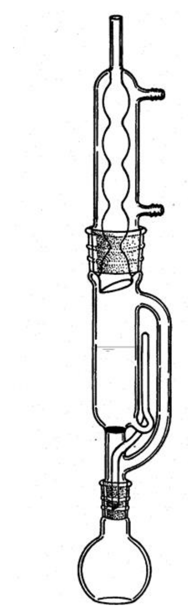
Details of the Soxhlet Extraction Material Compatibility Test can be found in various publications. What differentiates it from more common test methods, such as the ASTM soak tests mentioned earlier, is its ability to simultaneously measure both the mass of fluid absorbed by the polymer and the mass of the material that could be extracted from it. This makes the Soxhlet test more useful for assessing material compatibility in immersion cooling, particularly for two-phase systems.

For single-phase applications, the boiling temperature of the fluid is typically hot enough (130C or higher) to "burn" most organic materials and it does not simulate well the end-use operating temperature. For those reasons, one typically does not run the Soxhlet extraction test with the actual working fluid for single-phase applications.

Fluorochemical fluids (PFCs) with lower boiling temperatures can be substituted, in this case, to allow lower test temperatures. This practice is defensible because smaller PFC molecules are more able to get into a polymer (absorption) and are better solvents for extracting materials than their larger cousins. Their use therefore represents a "worst case."

2.6 Experiment Method

The Soxhlet extraction compatibility test is intended to quantify compatibility by measuring the ability of the fluorinated fluid to extract relatively non-volatile materials such as oils from the sample and the ability of the sample to absorb the fluorinated fluid under atmospheric reflux conditions in a Soxhlet extractor. Its ability to separate extraction ($me\%$) and absorption ($ma\%$) makes the Soxhlet test more useful for assessing compatibility than conventional soak tests which provide only an overall mass change. 48-hour Soxhlet extraction test gives "worst case" results at fluid boiling point.



2.7 Evaluation method

a) weight loss (extracted);
b) weight gain (swelling).

2.8 Meaning of the test results, extractables

Extractable materials should be as low as possible in the sample. <2% loss by mass indicates good compatibility, too much mass loss can change the dimension, May also make the material brittle and crack; Too much material loss can cause problems elsewhere in the system. This guideline is based on the multiple criteria including it should not change physical material properties to an appreciable amount and loading and efficiency of the filtration media. (Source: 3M)

This interpretation of the Soxhlet test results is a general recommendation to help the system engineer to design correctly. Please consult with supplier tech support for your specific application. It is recommended to have the proper filtration system to mitigate any extractables.

3. Thermal Design

In Immersion, heat is transferred by a fluid flow or phase change of the fluid over the hot components. This fluid flow is generated by either forced convection, when the flow is generated by an external force such as a pump, or by natural convection, where density variations are used to generate the flow. Natural convection plays only a minor role in most sealed chassis single-phase immersion configurations but must be considered in open bath systems. The density of the dielectric fluid at high temperature is lower than the low temperature density, which causes the high temperature fluid to rise and generate a flow. A passive 2-phase immersion cooling system is one in which heat generating electronics are immersed in a bath of dielectric coolant that boils on the heat generating devices. The heat is captured efficiently as saturated vapor and can be transferred efficiently by condensation to an external heat sink like air or water.

In single-phase immersion, to generate optimal and efficient cooling one maximizes the flow rate through the heat sink and over hot components with the strictest cooling requirements. The dielectric fluids are more viscous than air, which makes the generation of a turbulent flow more challenging. A turbulent flow is more efficient in removing heat than a laminar flow. However, there might be opportunities for enhancement by generating an unsteady versus a steady laminar flow. The unsteady flow may assist with breaking up the thermal boundary layer and therefore enhancing the heat transfer capabilities. Importantly, a flow is generated either by forced or natural convection in immersion but heat still needs to be extracted from the immersion solution. The extraction is accomplished through a heat exchanger or a condenser to ensure continued cooling.

The type of boiling that occurs in a passive two-phase system is most often called saturated pool boiling because it occurs within a pool of fluid uniformly heated to the fluid's saturation or boiling temperature with saturated vapor above that fluid. Direct submersion of a bare die or lidded package is rarely an optimal way to do two-phase immersion. Various techniques can be used to enhance boiling heat transfer: extended surfaces like metallic or graphite fins or foams function primarily to spread heat to a lower heat flux thereby reducing the wetted surface superheat, porous organic coatings and porous metallic coating (preferred today).

3.1 Heat transfer optimization

Whether a component is installed in a single- or two-phase solution, high power components such as a GPU or CPU will run much more effectively at lower component temperatures. Heat transfer enhancement is necessary around these vital devices.

With immersion cooling, a dielectric fluid is in contact with the entire IT gear and its printed circuit board, and this fluid creates a thermal pathway for cooling of all components. Therefore, many low power components that may require a heat sink in air cooling, can be cooled in immersion without a heat sink.

The importance of ensuring a thermal pathway is highlighted in the example of full fluid cooling using cold plates, where no air cooling is present [5]. For immersion cooling, it is the opposite. Indirectly-cooled components have a threshold value higher than for air cooling, since fluids are a more efficient heat transfer medium than air. Low power components such as Voltage Regulators (VRs), chipsets, Baseboard Management Controllers (BMCs) and embedded GPUs may not require heat sinks in immersion.

That said, the threshold power limit where thermal solution is not needed because of immersion should be evaluated on a case-to-case basis.

3.2 Single-phase heat transfer optimization

Note: The following paragraph states many properties of fluids. Unless specified, room temperatures may be assumed.

Common single-phase dielectric fluids have specific heat properties ranging between 1300 J/kgK (Fluorocarbon) and 2300 J/kgK (Hydrocarbon), while air has a specific heat value of 1000 J/kgK. For reference, water has a specific heat value of ~4180 J/kgK.

As the specific heat metric suggests (J/kg*K), the specific heat relates to the weight (kg) of the fluid. This is where the density of the fluid is of importance.

The density of the dielectric fluids is much higher than air. Therefore, combining heat capacity with density provides an insight in how fluid cooling affects heat sink designs. The relevant information here is the amount of energy which can be absorbed by a certain volume of the fluid. It should be noted that 1 Watt equals 1 Joule per second (1 Wh=3600J). The result of this is a much smaller surface area requirement for heat transfer within fluid as compared to air.

The following table describes the different heat capacities of the main dielectric fluid groups and how the heat capacity relates to its ability to absorb thermal energy per liter. Note the near identical thermal capability of Hydrocarbons and Fluorocarbons in this comparison. This is explained by the higher density of Fluorocarbons which compensates for the lower heat capacity, which is related to mass instead of volume.

Figure 10- Comparison of heat capacities amongst fluid groups

Medium type	**Specific heat**	**Volume/kg**	**Joules/litre**
Water (reference only)	4182 J/kgK	1 L	4182 J/L
Hydrocarbon	2300 J/kgK	1.24 L	1854.8 J/L
Fluorocarbon	1300 J/kgK	0.71 L	1831.0 J/L
Air	1000 J/kgK	773.46 L	1.3 J/L

Notes to this table:

- Even though water is not a suitable medium for immersion cooling, it is included in the table to provide a frame of reference.
- All specific heat numbers of used cooling mediums are rounded and generic to prevent specific fluid references.

3.3 Flow rate differences

Immersion in dielectric fluids can allow for greatly reduced heat transfer surface areas as the fluids are able to transfer heat much more effectively than air.

It is however not simply a matter of stating that the surface area can be reduced with a factor of 1400 (1831/1.3) as this would require identical flow rates to air cooling. The higher heat transfer capability of the dielectric fluids compared to air means that the flowrate can and will be greatly reduced. Thus, the thermal designer must balance the reduced flow rate with the required heat transfer surface area.

To properly design a heat sink for single phase immersion, a multitude of parameters should be considered for each type of dielectric fluid. In some cases, the target operational temperature may play a role in heat sink design as the fluid may show significant property changes when temperatures are changed (e.g. density, viscosity, specific heat, etc.)

3.4 Single-Phase heatsink design parameters

The first element which should be considered is the thermal resistance for the heat sink design to determine effectiveness of the thermal solution. If efficient cooling is obtained with the initial design, no redesign is needed. However, if an optimized solution is preferred, modifications to the heat sink design might be required.

Compared to traditionally used heat sinks for air cooling, immersion heat sinks will benefit from a larger fin pitch due to the increased viscosity of immersion fluids compared to air. The pitch is the distance between two separate fins. The pitch is mostly affected by the viscosity of the dielectric fluid which is used. The viscosity indicates the ease with which a fluid will flow.

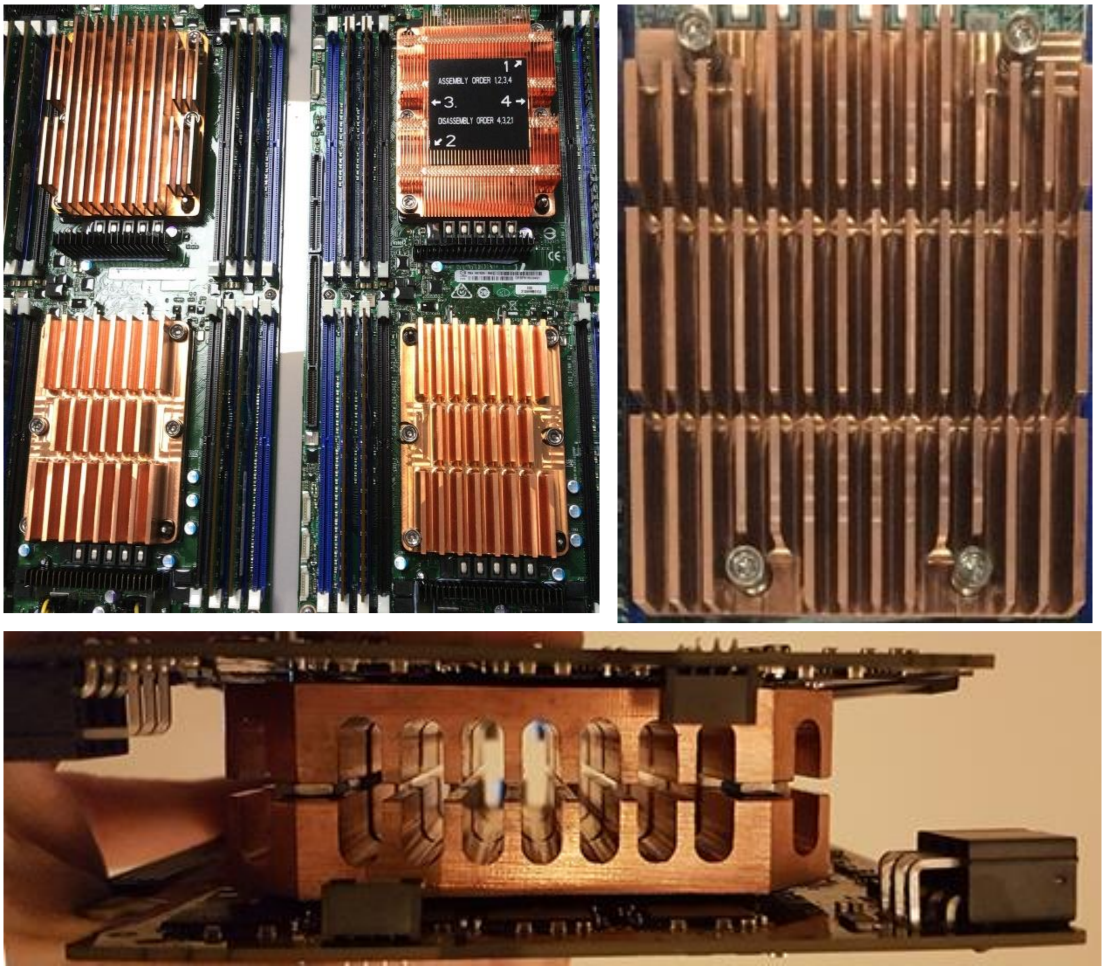
The fin specification is a very important aspect of heat sink design in fluid. Because of the high heat capacity of the dielectric fluid, heat is transported away from the fins effectively. The use of measurements and CFD (Computational Fluid Dynamics) for analysis is recommended. To maximize the effectiveness of the heat sink surface area, the thermal energy needs to be able to travel through the fins. Sufficient fin thickness should therefore be considered. Combined with the fin thickness, other fin properties like height and length can usually be drastically reduced to allow significant space optimization within the chassis.

The base of the heat sink is just as important as the fin specification as the base is responsible for distributing all thermal energy to the fins. In some cases, a solid metal plate may be enough for heat spreading while in other configurations the heat sink may require heat pipes or vapor chambers to effectively spread the heat in the base across the fins.

Some examples of fluid optimized heat sinks for open bath systems can be seen in the following images:

Figure 11- Comparison of heat sink designs

Heat sink examples

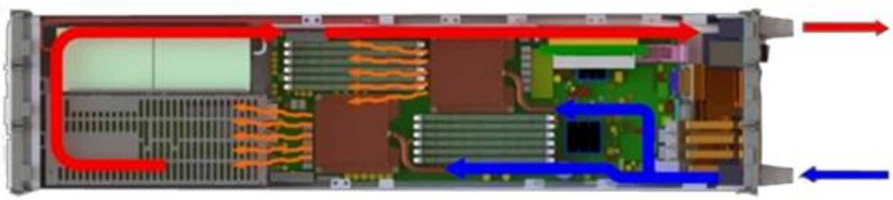


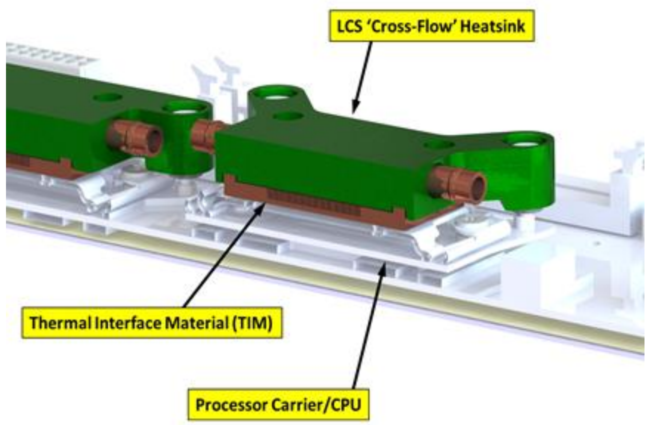
by Asperitas

Top left image	Top right image	Bottom image
Fluid heat sink test setup for Intel® Xeon® Scalable processors.	Exaggerated application specific fluid heat sink for AMD EPYC™.	Application specific fluid optimized heat sink for dual GPU sandwich.

Heat sink designs for sealed chassis configurations can take the form of a cold plate if forced convection is used to direct dielectric fluid to the hottest components. The following image is an example of how a single-phase sealed chassis system can work:

Figure 12- Cold plate in immersion

<table>
<tr><th colspan="2">Sealed chassis immersion cold plate</th></tr>
<tr><td colspan="2">




by LiquidCool Solutions
</td></tr>
<tr><td>Top image</td><td>Bottom image</td></tr>
<tr><td>Enclosed server cross section illustrating fluid flow through directed flow cold plate.</td><td>All components including processors, PSU, memory and storage are immersed in the dielectric fluid, but the entering fluid is directed to the processors first before being vented to the dielectric in the surrounding enclosure.</td></tr>
</table>

3.5 Two-phase heat transfer optimization

For optimal performance in two-phase immersion, any device (CPUs, GPUs, some ASICs, FPGAs, etc.) that would require a copper heat sink in an air-cooled and/or a single-phase immersion-cooled environment should have a boiler assembly applied to it. Typically devices (Surface mount voltage regulators, thru hole MOSFETs, diodes, some ASICs) that would have an extruded aluminum heat sink in an air-cooled environment do not require boiling enhancement. There is merit to providing boiling enhancement of some kind (Paint on organic BECs) for higher power (~30W) bare die devices.

3.6 Two-Phase Boiler Assembly

Heat spreader typically copper for its high thermal conductivity. Area and thickness dictated by heat spreading requirements.

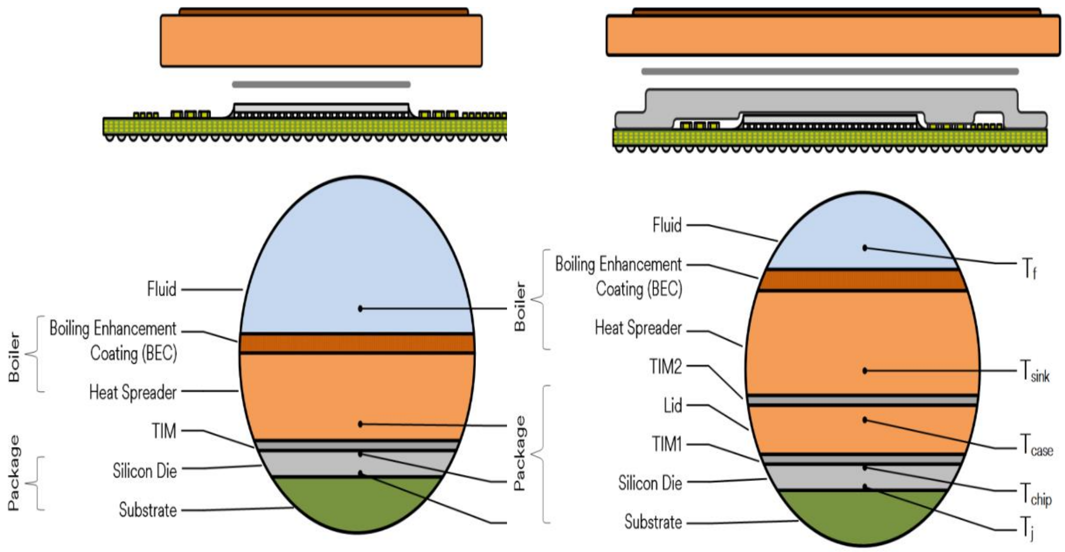
Boiling Enhancement Coating (BEC) typically, porous copper as described below and applied to a heat spreader. The thermal performance of higher power devices such as CPUs and GPUs are improved using boiling enhancement coatings (BECs). BECs can take various forms but are typically micro porous copper coatings 100-500 micron thick. BECs can provide up to a 15x increase in boiling heat transfer coefficient versus a smooth surface. BECs are often applied to a copper heat spreader to create a BOILER that can be applied to the CPU or GPU with various thermal interface materials or without a retention mechanism.

Retention Mechanism applies force to the boiler to ensure a good thermal and/or electronic (socket) interface. Retention plate is typically made of aluminum or steel. May or may not be bonded to Boiler. May include springs, screws, etc. to apply force to the Boiler.

Thermal Interface Materials (TIMs) are used to reduce the thermal resistance between two components, such as CPU/GPU and heat sink/BEC. There are many different types of TIMs available, and in this document they are divided into two main groups: solid TIMs and non-solid TIMs. Solid TIMs can be made out of metal, while the non-solid TIMs can be for example thermal greases. It is important to choose the TIM material carefully in immersion. One consideration is to ensure that the TIM selected reduces the thermal resistance sufficiently to meet the thermal requirement of the component being cooled (in the same way as done for air and cold plate cooling). In immersion, it is also essential to ensure material compatibility between any materials used in immersion and the immersion fluid, also for the TIM. In many immersion applications, solid TIM such as Indium foil is used and preferred.

Figure 13- Boiler plate assembly

Boiler assembly terminology

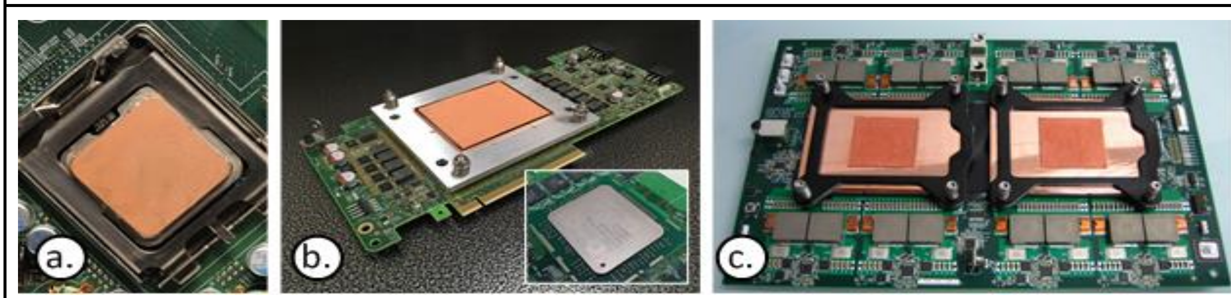


By 3M

Left image	**Right image**
Terminology for boiler assemblies applied to bare die.	Terminology for boiler assemblies applied to lidded devices.

Figure 14- Boiler plate assembly in situ

Boiler assembly example

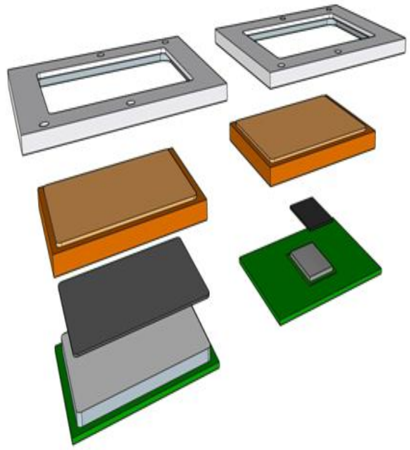


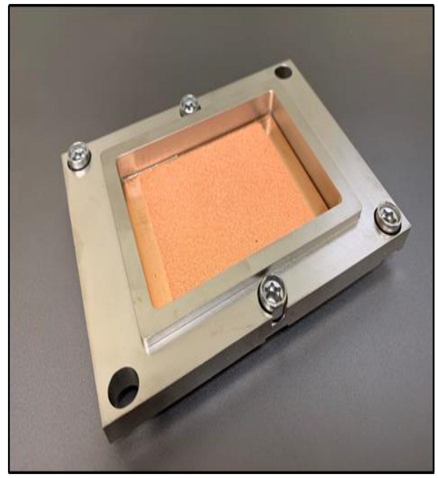
By 3M

a. BEC soldered to HIS;
b. BEC boiler applied to lidded GPU with thermal grease;
c. BEC boilers applied to 750W ASICs with Indium TIM.

Figure 15- Boiler retention plate assembly

Retention plate examples





By 3M

Left image	**Right image**
Exploded view of boiler and retention plate applied to lidded and bare die devices with a thermal interface.	Boiler assembly for Intel Skylake including plated aluminum retention plate, screws, etc..

3.7 Component placement for Single Phase fluids

Just like in air design systems, the layout of all electronics should be considered in accordance with their heat dissipation (TDP in Watts) and maximum temperature tolerance requirements (X°C) in relation to the fluid flow direction.

Components which generate more heat and/or require lower operating temperatures should be placed upstream or in the coldest/lower part of the tank. Components with a high tolerance for heat can be placed downstream or in the highest parts of the tank. The middle area can be filled with all remaining components, while considering any thermal component constraints.

The thermodynamic properties within the chassis are not only dependent on the thermal production within the chassis or tank, but also on total thermal production within the rest of the immersion system and the properties of the cooling supply. This means that IT systems can influence each other.

The flow direction in combination with component placement should also be considered carefully. Thermal shadow effects may impact the desired operation of components, while in other situations may be desirable to allow flow optimization.

T0: Bottom section/cold is where the dielectric fluid temperature is predictable and has a direct relation with the FWS cooling temperature. Since the FWS is used to cool the dielectric fluid by means of a heat exchanging device, there is always some kind of temperature difference or Delta (ΔT) between the dielectric fluid and the FWS. Since this ΔT differs between immersion technologies, it is important to understand this value if systems are designed for specific FWS supply temperatures.

This is also the area which is usually considered for GPU’s (high TDP), PSU’s (Temperature tolerance) or SSD’s (Temperature tolerance).

T1: Center/moderate is the area where the dielectric fluid is pre-heated by the most sensitive or highest performing components. The environment temperature in this position is usually higher due to this pre-heating. The actual temperature depends on the components within the bottom section.

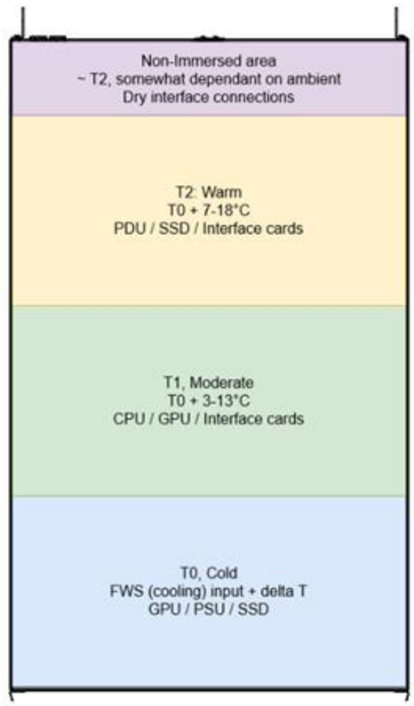
This area is commonly used for CPU’s and all components which are integrated or attached to the mainboard.

T2: Top/Warm the top of the system should have the highest temperature tolerance, as this is the area where hotspots may be encountered. Any heat which is generated by any component in the chassis will move upwards naturally. This means that this area should only be populated with components which are suitable for operation in the highest possible temperatures for the designed IT assembly.

This area is usually populated with PSU’s (ease of access), SSD’s (temperature tolerance/low TDP) and interface cards (temperature tolerance/low TDP).

Figure 16- Stratification of immersion temperature zones

Immersion temperature zones



Open Compute Project: Open Cassette Specification

Temperature stratification of immersion bath system example to consider IT equipment component placement.

3.8 Component placement for Two Phase fluids

Two-phase immersion cooling provides an isothermal environment in the tank, therefore thermal shadowing is not relevant, at least not at the densities reached today. In two-phase immersion, there is no significant role for stratification. Instead, consideration must be given to the spacing of components in the upper fluid Area to allow an escape path for the vapor produced by the phase changes of the components housed at the lower fluid levels. The total free-space throughout this area is determined by the amount of fluid which phase has changed, as a result of the power used by the operating components in the lower regions, and the difference in enthalpy of the fluid vs. the vapor phase of the fluid used. In general components which generate more heat and/or require lower operating temperatures could be placed at the bottom of the fluid.

4. Mechanical Design

4.1 IT chassis dimensions

Single-phase sealed chassis servers can be sized to fit into standard OCP racks. For open bath systems the chassis design depends on the dimensions of the tank that is being used. To be consistent with air-cooled servers, the 19-inch and 21-inch server widths will be addressed in this section. Other chassis widths are possible and will have their advantages and disadvantages and can be used as necessary.

Since the 19-inch form factor is still largely used in data centers and the 21-inch form factor is being deployed at an increasing rate, both are adaptable to immersion without requiring a huge redesign effort.

The dimensions of the chassis should allow for easy installation of components while keeping the highest possible density.

The length of the chassis is related to the depth of the tank. The length of the chassis should allow for easy extraction/removal from the tank.

Considering the different compute requirements from users, immersion cooling is a good solution for high density IT equipment. To keep the height of the chassis as small as possible, components of lower height can be considered. The height of the DIMMs can also be a limiting factor in system U-height. Thus, options for reduced DIMM height such as angled connectors or short DIMM may be desirable.

In open bath systems the servers are immersed in a dielectric fluid, and a minimum space between servers (e.g. 0.5-mm) is recommended to facilitate extraction and avoid the adhesive force effect.

4.2 Chassis consideration for immersion

For vertically-oriented tanks (open bath), these features on the chassis need to be considered in order to improve installation, handling and the serviceability:

c) At least one handle or other hoisting features to assist when pulling out the chassis vertically, preferably that may be used both by hand or an assisted lifting device;
d) Support vertical pulling forces by for example reinforcing the front or rear of the chassis, where the handles are fixed;
e) Guiding features should be considered to help control the lowering of the chassis into the tank and to keep its designated position;
f) Features that allow for the reduction/elimination of unwanted movement e.g. shake effect once installed in the tank;
g) In vertical orientation of the chassis, fixation features for add-on components installed (e.g. PCI cards, extension boards etc.);
h) Component orientation that will not block thermal flow. For example, the components that are fitted with a heat sink should be placed with the heat sink fins parallel to the thermal fluid flow;
i) If mounting ears are designed, these should be removable to allow positioning in vertical tanks.

The compute unit can be powered on by power cable or busbar:

a) Cable access from the top of the tanks is highly recommended to allow an operator to unplug all cables before servicing the chassis. The features for cable management, such as cable trough, cable duct, are recommended to optimize the cable routing;
b) If in a busbar implementation, the blind-mate busbar clip must be floating and requires guiding features to facilitate the alignment tolerance between the chassis and the busbar.

Concerning the mass of a chassis, the maximum load for operator servicing should be considered to decide the maximum weight of the server. In order to meet data center handling requirements, the total mass of a server with all the components installed are preferred to not exceed 34 kg (75 lbs.). Even more, if the server is more than 18 kg (40 lbs.) it is recommended to be handled by two people [7]. In order to have a better understanding of the total mass of a server that can be safely handled, considering the immersion environment constraints (e.g. the hydrocarbon-based fluids are known to be slippery), further research or information from the industry is required.

4.3 Power Supply

Most open frame AC/DC power supply units (PSUs) can be suitable. A regular server PSU may require modification to allow long-term operation without fans and with sufficient fluid flow. Because PSUs often have a built-in thermal shutdown feature based on an air-cooled scenario, they may initiate a power-off at too low temperatures in immersion systems. Modifications in either software or hardware may be required to optimize or turn this feature off. A PSU Backplane can be included into the chassis design to allow for a redundant power setup.

In single phase or 2-phase applications, dedicated PSU and shared power (power shelf implementation) are feasible, depending on the tank configuration. The tank could be fitted with busbars or power cables for the power distribution. Reducing the I/Os through the tank should be considered to achieve better sealing of the tank lid.

In-chassis placement:

PSUs installed in the chassis (e.g. 19'' standard build) must be fully immersed. For optimized cooling in single phase systems the PSU should be installed in the lower part of the chassis, near the bottom of the tank to avoid preheat effects. Installing the PSU in the upper part of the chassis is also an option, with the added advantage of offering accessibility to the PSU for replacing or maintenance purposes.

Specifically, in single phase systems, when considering the PSU location in the chassis, one should consider the preheat impacts on components in the downstream flow path. For example, flows exiting CPUs, GPUs, or other high-power components will be preheated. These higher temperature flows may create cooling challenges for components in the downstream flow path.

Power shelf configuration:

PSUs located in a power shelf offer the ability to share the energy requirement, among a specified number of nodes, via bus bars or power cables (e.g. OCP solution).

One of the advantages of this solution is that, by removing the PSU from within the chassis the extra space can be used for additional IT gear or for reduced space for fluid savings.

The power shelf should be installed in a way that allows for easy access and removal of the power modules. For example, in a vertical orientation, with the power modules accessible from the top of the tank.

If the tank is fitted with busbars, special attention should be given in positioning them out of reach of the operator and to protect them from possible falling debris.

For both options, dedicated PSU and power shelf configuration, it is important that the fans are disable (e.g. via software control), unplugged or physically removed in order to avoid the alteration of the predefined fluid flow.

4.4 Storage

Direct immersion of storage devices is limited to SSD/NVMe (chip) and sealed helium drives. Storage can be included by using brackets for mounting storage devices into the chassis. While acoustic waves may be a consideration for spinning drives in air environments where fans are present, early data from hard drive liquid immersion studies have shown a substantial improvement in tracking and random performance capability. However, the acoustic wave effects in high throughput systems with both compute and storage components have yet to be evaluated for potential benefits. Nevertheless, acoustic wave considerations should be a design factor in the development of immersion systems [20].

4.5 High speed (optical) network cabling

High speed or high-performance network cabling based on copper can normally be used within the chassis.

When an optical cable interface is immersed in dielectric fluid, the air at the interface (between ferrules) may be replaced by the fluid. This interface change results in signal reflection loss due to the change in refractive index (RI) at the optical interfaces, which should be considered during the design process of an IT solution.

There are several commonly applied solutions to deal with this constraint:

1. Use of cables with direct attached connectors like SFP or QSFPs which:
    a. Contain no air gap. These cables could be soldered or glued to the transceiver which eliminates the possibility of signal reflection loss;
    b. contain sealant to prevent fluid penetration into the air gap;
    c. Connectors using silicon photonics have no air gap.
2. Use port extenders to allow optical connectivity outside of the fluid environment.

5. Electronic Design Guidelines

5.1 Reference for Signal Integrity (SI) Verification

Signal integrity of a circuit or system should be validated when using immersion technology. A thorough and rigorous analysis is the only way to validate that a successful outcome is likely. To help validate the signal integrity in immersion cooling, the measurement of an eye diagram should be part of the test plan and designed to meet the high speed I/O specification. An eye diagram is a common indicator of the signal quality of high-speed digital transmissions.

PCIe	Transfer Rate (GT/s)	Eye Height (mV)	Eye Width (UI)
Gen 3	8.0	>34	0.33
Gen 4	16.0	>19	0.352
Gen 5	32.0	>17.5	0.31

Note: This is an eye mask for PCIe CEM form factor. Different platform form factor may have different testing eye mask requirement. They should all follow the base specification requirement and end to end link margin requirement. Some examples are the PCIe CEM specification [17], PCIe base specification [18], and OCP NIC 3.0 specification [19]

SI test:	
Check the S parameter to ensure any signal insertion loss and differential impedance is within the specification. Check the eye diagram to ensure the signal integrity is within the specification. The experiment should follow the following steps: (Use PCIe CEM test item for example). It is recommended that the test set-up be validated prior to immersion.	
Goal:	**Evaluation method**
To test the signal integrity (S parameter) of the electrical design while functional in a dielectric fluid.	Assemble the Device Under Test (DUT) and connect the test fixture. Turn on and set the oscilloscope to default settings. Turn on the DUT. Load the pattern generator tool and generate the test pattern signal. Capture the signal and save it as binary file (.bin) by using the oscilloscope. Test the saved waveform by using software SigTest. Check the test result and make sure the result is within the specification.

PCIe host and card compliance test procedure can be found at https://pcisig.com/developers/compliance-program

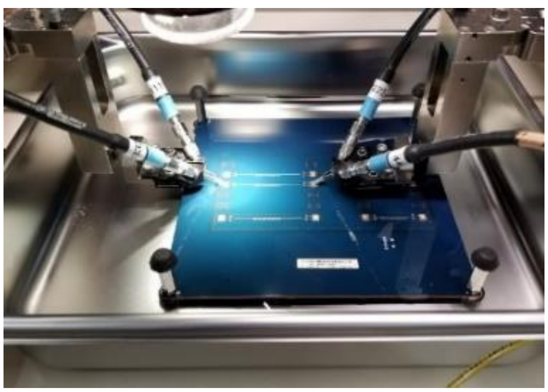
5.2 Signal Integrity Verification Design Consideration for Immersion

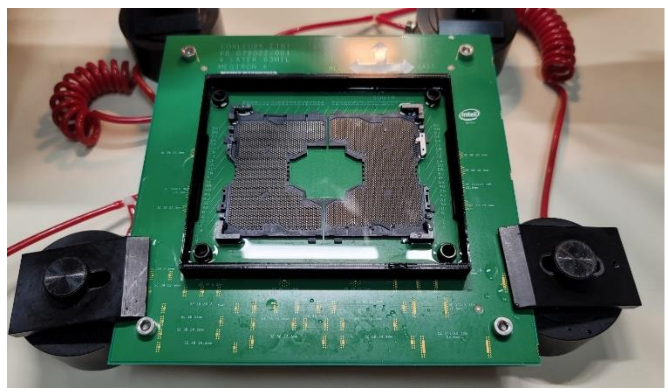
Dielectric constant Dk shall be considered along with other channel performances to meet socket and connector impedance requirement for High-speed I/O interfaces.

The impact of immersion to the PCB transmission line needs to be evaluated and that includes several different considerations.

The impact to microstrip insertion loss needs to be considered. Generally, the insertion loss increases slightly increases, with no significant impact to microstrip loss. However, the designer can minimize high-speed signal routings in microstrip from the beginning of the design. The full channel simulation analysis should be performed when the total channel loss is at the design edge of server platform design guidance. The following figure shows measurements of PCB transmission line insertion loss.

SI measurement examples





By Intel

Left image	**Right image**
PCB transmission line insertion loss measurement when immersed in fluid.	Socket and package substrate measurement diagram when immersed in fluid.

The impact to microstrip impedance needs to be considered. Microstrip impedance can be reduced due to the property of immersed media versus air. It is recommended to consider this when specifying PCB impedance for manufacturing. The chemical properties of the immersion fluid used needs to be evaluated to determine impact. The impact to microstrip crosstalk needs to be considered. Far-end crosstalk effect is typically reduced, while a near-end crosstalk effect is not obviously observed.

Generally, there is no significant impact to strip line loss, impedance, and crosstalk.

The connector and socket typically are designed with air as surrounding medium. When immersed in fluid, the design target impedance will likely be changed. New models with surrounding air replaced with fluid should be created, and performance impact needs to be understood.

There is a potential for the mismatch of capacitive impedance and conductive impedance of the socket to be balanced by the fluid. In general, this effect is not expected to significantly impact the channel performance. For the future socket design, the analysis should be performed to check the immersion impact to SI performance.

Most connectors tuned for air use may fail due to the capacitive impedance mismatch increased and the inductive impedance mismatch reduced when connector is immersed in the fluid. It is recommended to evaluate the fluid impact during the design.

Cables also pose a performance challenge. High speed cables for Ethernet, PCIE, etc. have stringent performance specifications. Small changes may have big performance impact. For example, there is a potential risk for fluid to be wicked up the cable sheathing changing its performance. Cables should be tested for long term electrical performance and reliability.

	Loss	**Impedance**	**Crosstalk**
PCB Microstrip	Less loss, may be due to lower humidity content	Will be lower in reference to air	Lower FEXT; Little NEXT impact
PCB Strip line	Stable loss	Little impact	Little impact
Package and socket	No significant impact	No significant impact	FEXT from socket slightly increase; No significant NEXT impact
Connector	More loss at high frequency, due to more reflection	Significantly lower impedance peak; Significantly more return loss	No significant FEXT and NEXT impact, due to impedance delta, considerations should be made for reflections

As fluids age there are potential that the material properties will change, hence changing the SI performance. Potential changes that may occur are chemical property changes, external environment contamination, internal component material washout contamination etc. Contamination from internal or external sources can create electrical performance issues and can all contribute to signaling performance changes. Proper cleaning of components for initial deployment, filtration system, and continuous monitoring of the fluid properties should be considered. It is recommended to periodically check fluid electrical property to ensure they are within specified range.

5.3 Adjustable temperature settings

Many systems are equipped with a thermal sensor which is used to determine the environmental temperature of the IT equipment. The firmware monitors this sensor and determines whether it is safe to switch on.

Since immersion can work with much higher temperatures compared to air and the solutions vary in thermal effectiveness and tolerances, this temperature threshold should be a configurable item for immersion solution vendors, IT integrators, or end users.

Alternatively, an option to disable the platform thermal protection should be considered which allows fallback to integrated thermal management of chips.

Many components are monitored for their thermal status during operation. When implementing IT equipment in immersion, these tolerances may be impacted. Some sensors may be set to higher tolerances and others should remain unchanged.

An alternate set of temperature thresholds should be available to integrators and end users when implementing IT in immersion to facilitate optimized thermal monitoring.

5.4 Fan control and detection

Most electronics are initially designed for air and manage the airflow in the system. Combined with airflow management, there are often safety features to prevent server activation without fans present or while fans are disabled or defective.

Since fans are not supported in most, if not all immersion strategies, any airflow management should be disabled. Any safety controls related to airflow like fan detection must be disabled and this should not trigger any alerts.

5.5 System performance

Immersion allows more efficient cooling compared to air. For this reason, an IT system has the potential to operate on higher performance for longer time periods. The firmware should allow for continuous operation in turbo mode or even allow overclocking. Settings for this should be facilitated to at least immersion solution vendors and IT integrators.

5.6 Management reporting (IPMI)

The management port of a server allows access to remote control features and status reporting of the server system. The telemetry which is generated by air designed systems is based on basic system information and its condition in an air environment.

5.7 Immersion support in firmware

For business economics reasons, IT equipment will most likely be designed for air and compatibility with immersion. For this reason, the firmware may include a set of thresholds and settings which are optimized for immersion. Examples of methods allowing to switch between air and immersion are:

a) BIOS switch for immersion. The default mode may then be air, but when immersion is selected, all thresholds, safety features and performance settings are optimized for immersion. This means that immersion becomes part of the standard firmware of every system. Further specifications could be considered to differentiate between specific immersion solutions (brand/type) or immersion categories (single phase vs 2-phase)
b) Custom firmware. Custom firmware may be further optimized for immersion and could also be made specifically for a specific immersion solution or a range of solutions. This custom firmware solution should be made available to Fluid solution vendors and IT integrators.

Appendix: Common practices dealing for retro-fitting air-designed IT equipment

1. Disconnect any fan and, if necessary because firmware can't operate without it, connect a fan emulator to supply the required pulses and pretend a correct fan is functioning.
2. Replace thermal paste with either a type compatible with immersion or another TIM suitable for immersion (e.g. Indium Foil).
3. Check whether PSUs contain solenoids or relays which might not be operable while submerged.
4. Ensure no spinning drives are immersed except the helium sealed type. SSDs do not suffer from incompatibility issues due to their absence of moving components.
5. If an off-the-shelf chassis is used, ensure the selection of a model whose brackets ("ears") are on the side which will be exposed at the top of the tank, or a model for which a different holding, securing and hoisting mechanism can be easily retrofitted.
6. Any system that will be immersed should be thoroughly cleaned from dust particles and other contaminants which might pollute the dielectric fluid.
7. For open bath configurations, whenever possible use servers with all available ports and connections on the "top" side of the server, ports at the "bottom" of the tank will not be easily accessible and, if cables are required to be connected there, the cabling will be complicated and potentially unsafe.
8. Cable routing is essential. The designer must be careful to ensure that the cables have enough length and space to pull out the chassis if they cannot be removed for servicing.
9. For testing purposes and reverse engineering, fan simulators may be used. Please refer to the OCP Fan Sim spec for more details.

Fan Sim specification: https://www.opencompute.org/documents/open-compute-specification-fan-sim-spec-2-pdf

Appendix: Glossary

BBU Battery Backup Unit

BEC Boiling Enhancement Coating: surface microstructure enhancing coating to improve heat transfer properties

CRAC Computing Room Air Conditioner

DC Data Center

DUT Device Under Test

EPDM Ethylene Propylene Diene Monomer: a type of synthetic rubber

HSC Hot-swap Controller

IPMI Intelligent Platform Management Interface: A set of computer interface specifications for an autonomous computer subsystem.

PCB Printed Circuit Board

PCBA Printed Circuit Board Assembly

PDU Power Distribution Unit

PSU Power Supply Unit

PUE Power Usage Effectiveness

PSU Power Supply Unit

QSFP Quad (4-channel) Small-form Factor Pluggable: A common optical component type for data center servers and other computing and communications equipment.

TDP Thermal Design Power value describing the thermal limits of a component or computer system

TIM Thermal Interface Material: any material inserted between two parts to enhance the thermal coupling

VR Voltage Regulator

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About Open Compute Project

The Open Compute Project Foundation is a 501(c)(6) organization which was founded in 2011 by Facebook, Intel, and Rackspace. Our mission is to apply the benefits of open source to hardware and rapidly increase the pace of innovation in, near and around the data center and beyond. The Open Compute Project (OCP) is a collaborative community focused on redesigning hardware technology to efficiently support the growing demands on compute infrastructure. For more information about OCP, please visit us at http://www.opencompute.org