White Paper

Communications Service Providers
Data Center Sustainability

Intel Collaborates with KDDI to Drive Sustainable Immersion Cooling Data Center Solutions

Intel, KDDI and ecosystem members conduct proof of concept (PoC) of Intel's immersion cooling reference design demonstrating how the system reduces energy in data centers reducing carbon footprint

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Table of Contents

Executive Summary................ 1

Test Environment with Intel Open IP Immersion Cooling Reference Design 2

Test Set-Up and Methodologies. . 3

Proof of Concept Results 5

Conclusion......................... 12

Executive Summary

KDDI Corporation (KDDI) is one of Japan's largest Tier-1 telecommunications operators. In the course of providing its customer services, the company consumes energy for its various data center operations which emits approximately one million tons of CO2 annually. To move toward carbon neutrality, KDDI is firmly committed to achieving net-zero CO2 emissions in its business activities by fiscal 2030.

KDDI has adopted several approaches to reducing emissions to achieve its target, including using the latest immersion cooling technology which uses less energy than the traditional air conditioning to cool data center servers. Immersion cooling helps KDDI counter the increased heat created by server CPUs, which have larger core counts and higher frequencies that drive a higher thermal design power (TDP) envelope.

One of the key challenges for KDDI in commercial use of immersion cooling technology is system level warranties from OEMs and immersion cooling vendors since the effects of operating servers fully immersed in coolant fluid are still being evaluated.

This PoC is the first step in KDDI's plan to test immersion cooling and disseminate test data to OEMs, component and immersive cooling vendor to further refine and build a robust ecosystem for next generation datacenters.

As an industry leader, Intel is designing its portfolio of products to be more sustainable but also undertaking a large number of initiatives to drive the future of sustainable computing. Intel is actively investing to enhance immersion cooling technologies for its portfolio of products by:

- Developing immersion optimized solutions – Creating a reference for immersion liquid selection, developing Intel products and system designs that are optimized for use in immersion cooling systems.
- Building an immersion compatible ecosystem – Collaborating with OEMs and immersion vendors to make it easy for customers to adopt immersion.
- Resolve issues with warranty under immersion – developing test methodologies for enabling warranty assurance under immersion for many Intel components.

About the Immersion Cooling PoC

To answer these questions and quantitatively demonstrate the possible benefits of immersion cooling, KDDI worked with Intel and cooling fluid supplier ENEOS Corporation which is largest energy company in Japan to conduct a proof of concept (PoC) of immersion cooling using 4th Gen Intel® Xeon® Scalable processor-based servers and ENEOS immersion cooling fluid. ENEOS optimized cooling fluid is compliant to Japan's "Fire Service Act" law and meets KDDI's long-term commercial use requirements.

The objective of the PoC is to test Intel® Xeon® Scalable processor platform reliability, compatibility with material, and conditions under immersion such as thermal efficiency. In addition, the PoC seeks to identify the server system level changes, like optimized heat sink design and immersion compliant thermal interface material (TIM) for commercial use and to collaborate with ecosystem members, such as ENEOS, to advance immersion cooling technology.

The PoC was successful in demonstrating that the immersion cooling system works very efficiently and provides insight into some of the considerations that need to be discussed and resolved for immersion cooling to become a widespread alternative. The rest of this white paper details the testing and results of KDDI's testing of the immersion cooling system with 4th Gen Intel® Xeon® Scalable processor-based servers.

Based on the positive results of the PoC, both Intel and KDDI agree that immersion cooling is a viable technology for data centers and that KDDI will aim to adopt it as part of its sustainability changes. Both companies are committed to applying what was learned to develop guidelines for system design, coolant fluid and growth of the ecosystem.

Test Environment with Intel Open IP Immersion Cooling Reference Design

Intel is embracing immersion cooling for data center and edge servers as part of the company's ongoing efforts to create sustainable data center technology. The company has launched its first Open IP immersion cooling reference design in Taiwan. The open and scalable total server cooling solution allows ecosystem members to accelerate the introduction of energy efficient immersion cooling solutions in response to the trend of increasing data center power density. Intel also plans to work with ecosystem members to develop and validate related solutions in the future.

Heat dissipation is another large power consumer after IT load and is also key to improving data center operational efficiency. Immersion cooling systems are either single phase or two phase. Single phase systems use convection heat dissipation of liquid flow to efficiently dissipate heat from the server, while two phase is based on the theory that boiling liquid can absorb more heat and can remove more waste heat in a timely and effective manner. This document focuses on single-phase only.

Intel's phase 1 data center immersion liquid cooling total solution uses single phase liquid cooling to immerse the server in a non-conductive liquid. A single tank can support 12U racks and 15kW power density and is internally compatible with both general purpose and modular server form factors and is scalable from edge to large data center accommodating 24U, 36U, 48U, and up to 54U server chassis.

How Immersion Cooling Works

Single phase immersion cooling utilizes a coolant with a high boiling point and that remains liquid throughout the heat exchange that takes place during the heat dissipation process. The server is always in contact with the coolant. The working principle of the single-phase immersion cooling system is based on the concept of thermal buoyancy to inlet the coolant liquid from bottom of the tank. After the coolant is heated by a heat source, such as a server, the density of the coolant decreases, and it moves up to the top outlet. The heated coolant flows to a coolant distribution unit (CDU) heat exchanging system that allows the heat collected by the coolant to be extracted for heat transfer through a water-cooled circuit. The cooled coolant is then pumped from the CDU to the bottom of the tank to repeat the closed-loop heat transfer.

Following the concept of thermal buoyancy, the server must be situated such that its high power or low temperature specification components are placed at the bottom of the tank, and the low power or high temperature specification components are placed on top. New modular server form factors are optimized to be more flexible, reusable, and scalable for immersion cooling.

Figure 1 shows the single-phase immersion cooling working principle with modular server design guide.

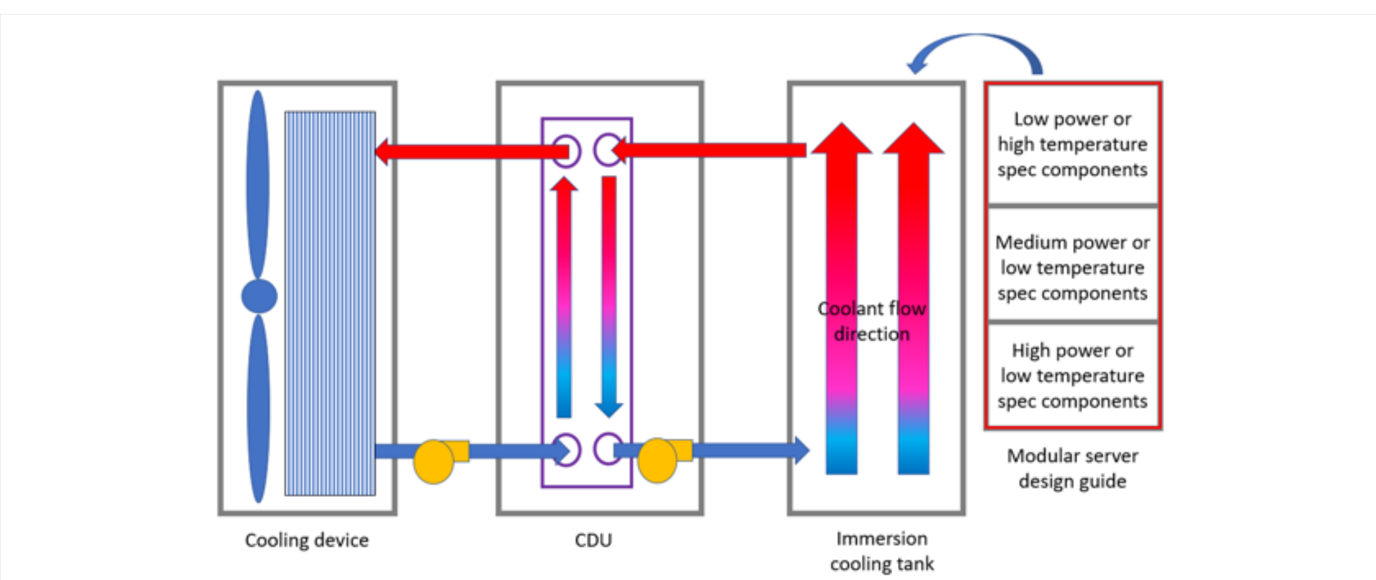


Figure 1. Single phase immersion cooling working principle with modular server design guide

	Test Items	Description
Server Tests		
1	Cooling Capacity	Validate the operation behavior of CDU to check that the actual cooling capacity meets the design
2	Server Thermal Performance	Ensure thermal performance under full server loading conditions
3	Server in Tank Signal Integrity	Test in-tank SI and compare results with air cooling SI results
4	Server in Tank Electrical Validation	Test in-tank EV and compare results with air cooling EV results
5	Server in Tank Heat Sink Verification	Analyze combination of simulation and experimental data for heat sink improvement
Coolant Tests		
1	Coolant Spec.	Coolant specification
2	Material Compatibility Verification	Verify that the server materials do not have any compatibility issue when immersed in this coolant

Table 1. Summary of test items for the proof of concept (PoC)

KDDI values immersion cooling as a key technology to increase cooling efficiency and to reduce energy thus carbon footprint at their datacenters. KDDI is aiming to adopt immersion cooling for long-term (approximately 7-8 years) use once it is able to get warranties from OEMs and immersion cooling vendors.

On the other hand, KDDI is facing challenges evaluating effects of long-term use of server components and coolants, material compatibility under immersion cooling environment, coolant suitable for commercial use.

Intel and KDDI discussed the test items for this proof of concept (PoC) and agreed on the plan shown in Table 1.

Test Set-Up and Methodologies

Server Test

(1) Cooling Capacity

The Cooling Distribution Unit (CDU) is designed according to the specifications of ENEOS immersion cooling fluid, and then uses experiments to verify whether the Intel Open IP immersion cooling reference design system delivers cooling capacity of 15 kW. Figure 2 shows the Intel Open IP 12U immersion cooling system with 15 kW CDU cooling capacity used in the experiment. The following test steps are used to verify the maximum cooling capacity of the CDU to check the cooling capacity to meet the design.

1. Using a dummy heater to simulate IT loading. In this white paper, three sets of dummy heaters are used for experimental verification, each dummy heater is 5 kW, and the total power loading is 15 kW. Figure 3 shows the placement of three sets of dummy heaters in the experimental equipment.
2. Set the CDU pump frequency to be fixed at 140 Hz.
3. After the immersion cooling system to achieve the conservation of energy, analyze primary and secondary measurement data to calculate cooling capacity.

Figure 2. The 15kW cooling reference design solution includes CDU on left and 12U immersion tank on the right

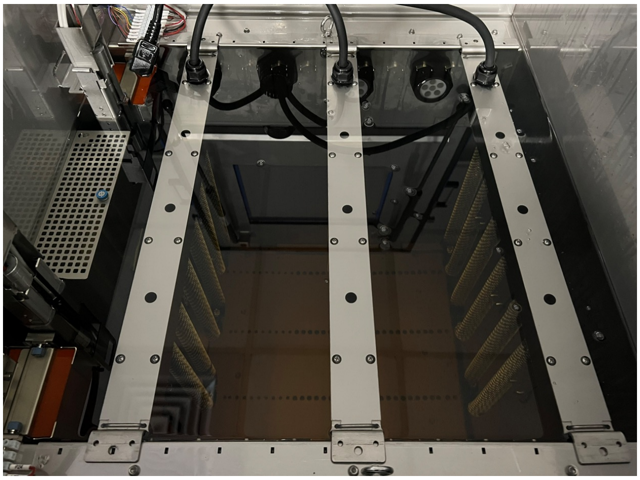


Figure 3. Three sets of dummy heaters are placed in the experimental equipment

(2) Server Thermal Performance

In order to verify the thermal performance of the server, the server must be tested under a full loading condition. The experimental method used a 2U modular server powered by 4th Gen Intel® Xeon® Scalable processor. Figure 4 shows this server and Table 2 lists the power consumption of the server's components for thermal performance verification. The following are the test steps for server thermal performance:

1. Immerse the modular server and dummy heaters to achieve 15 kW design.
2. Monitor the thermal variation of the server in the tank.
3. Monitor the behavior of each temperature sensor point to ensure the monitor system is functional.
4. Analyze the thermal performance of the server.

(3) Server in Tank Signal Integrity

The signal integrity (SI) tests in the testing fluid include time-domain reflectometry (TDR) impedance on differential and single-ended signals, and vector network analyzer (VNA) to measure the S-parameters. The SI tests are measured from

Figure 4. Intel 2U modular server chassis

20MHz to 20GHz. The impedance, loss and crosstalk are measured from the PCB test coupon both in air at room temperature and in the testing fluid after running 200 hours at tank operation temperature. The test result in the testing fluid will be compared to the in-air test result.

(4) Server in Tank Electrical Validation

The electrical validation (EV) tests for high-speed IO use the Intel® IO Margin Tool (IOMT) and Intel® DDR Rank Margining Tool (Intel® RMT) to measure the eye diagram margin of the server PCB board in air and in the testing fluid after running for 200 hours. The IOMT checks the PCIe/DMI/USB margins, and the RMT tool is for DDR5 memory margin test. Both test results in the testing fluid will be compared to in air test result after 20 test cycles (2 boards x 10 repeats) and will be referred to Intel high speed IO (HSIO) margin in air guideline to indicate signal health.

2U Modular Server Power Consumption

Major Component		Qty	Power (W)
Compute Node (per PCS)	CPU	4	1,080
	Memory, DDR5 DIMM	32	482
	PCH	2	60
	PSU	2	198
	NVMe SSD	2	50

Table 2. Power consumption of 2U modular server (2 servers)

(5) Server in Tank Heat Sink Verification

To optimize server thermal performance, a customized heat sink is used on the server. The design of the heat sink will be optimized for each environment according to the properties of the medium. According to the properties of the testing fluid, the heat sink design is optimized by simulation and compared with the traditional air-cooling heat sink. The following are the test steps for server in tank heat sink verification.

1. Use computational fluid dynamics (CFD) to design a suitable immersion cooling heat sink for use with the testing fluid.
2. Immerse the servers and verify air cooling and immersion cooling heat sink behavior.
3. Analyze and compare the test data.

Coolant Test

(1) Coolant Specification

As cooling fluid supplier, ENEOS provided its newly developed immersion cooling fluid for this PoC. ENEOS will also provide coolant specifications suitable for liquid immersion including viscosity, density, dielectric constant, and other properties.

(2) Material Compatibility Verification

During the coolant reliability testing process, there will be a verification that there are no material compatibility issues.

Proof of Concept Results

Server Test

(1) Cooling Capacity

The maximum cooling capacity is verified by using dummy heaters. The experimental method is to confirm whether the system is stable when the system load is 5-15 kW, the liquid flow rate is about 40 LPM, and the pump frequency of the CDU is fixed at 140 Hz.

Table 3 shows the cooling capacity test results. Figure 5 shows the relationship between the cooling capacity and the coolant inlet temperature as measured after the coolant and water heat exchange. When the system load increases, the coolant inlet temperature becomes higher, but it can still achieve a steady state and meet the maximum cooling capacity design of the system. As shown in these figures and tables, the maximum cooling capacity of the Open IP immersion cooling reference design is verified to meet 15 kW when the modular server components meet the temperature specifications.

Purpose		Validate the cooling capacity with ENEOS immersion cooling fluid in Intel Open IP 12U15kW immersion cooling system		
Test Location		Taipei		
Cooling Mode		Chiller		
Working Fluid Type		ENEOS immersion cooling fluid		
Dummy Heater	Node 1 Heater Power (kW)	*	5.31	5.33
	Node 2 Heater Power (kW)	5.27	5.27	5.33
	Node 3 Heater Power (kW)	*	*	5.38
	Total Loading Power (kW)	5.27	10.58	16.04
Coolant	Specific Heat (Calculated) (kJ/kgK)	1.9	1.9	1.9
	Viscosity at 40 °C (mm^2/s)	35.0	35.0	35.0
	Density (g/cm^3)	0.84	0.84	0.84
Secondary Side of Plate Heat Exchanger (Coolant Side)	TCoolant_in (°C)	32.4	35.4	38.5
	TCoolant_out (°C)	30.3	31.5	32.9
	Flow Rate (LPM)	68.2	72.9	76.0
Primary Side of Plate Heat Exchanger (Water Side)	Tw_in (°C)	29.8	29.8	29.0
	Tw_out (°C)	31.7	33.7	34.8
	Flow Rate (LPM)	39.6	38.8	39.5
CDU Pump	Pump 1/2 Frequency (Hz)	140 / 140	140 / 140	140 / 140
	Pump 1/2 Outlet Pressure (bar)	0.8 / 0.8	0.8 / 0.8	0.8 / 0.8
	Power Consumption (kW)	1.65	1.60	1.57
Ambient Temperature, Ta (°C)		27.4	27.4	27.6

Table 3. Cooling capacity test results with the testing fluid in Intel Open IP 12U15kW immersion cooling system

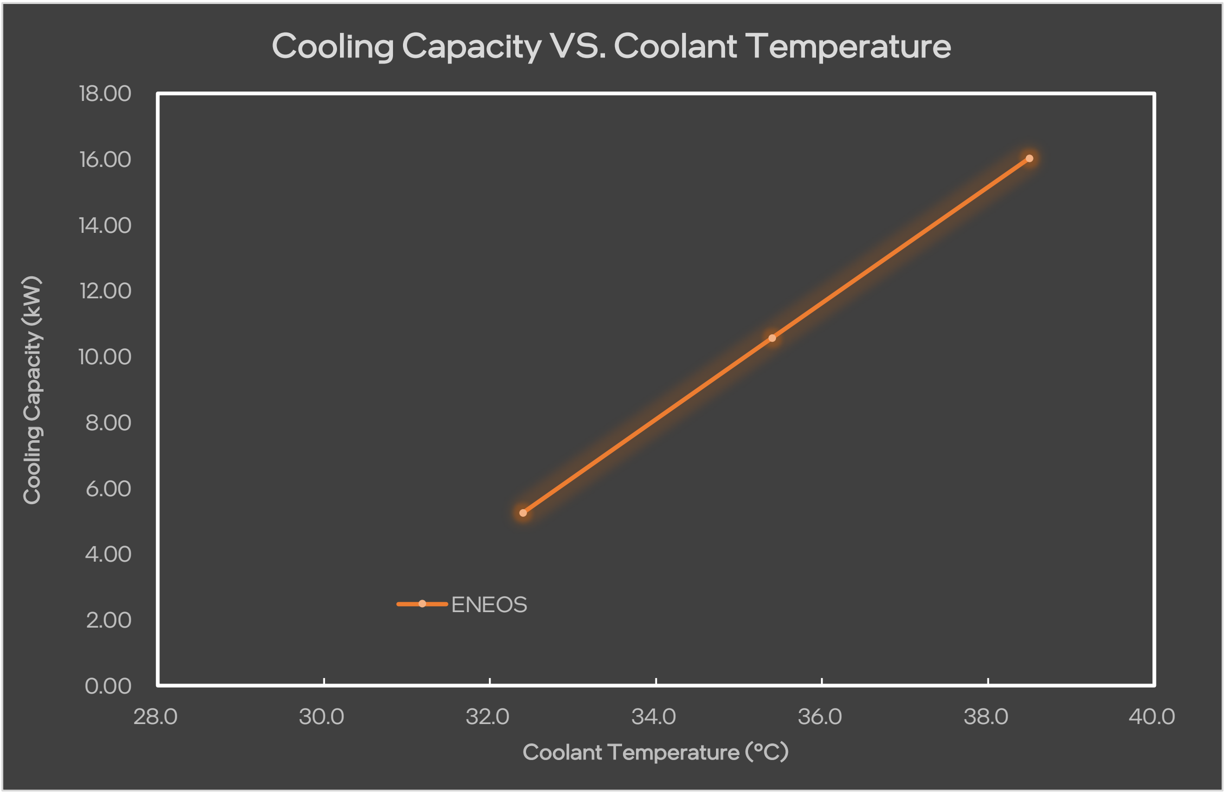


Figure 5. Cooling capacity and coolant inlet temperature test results

(2) Server Thermal Performance

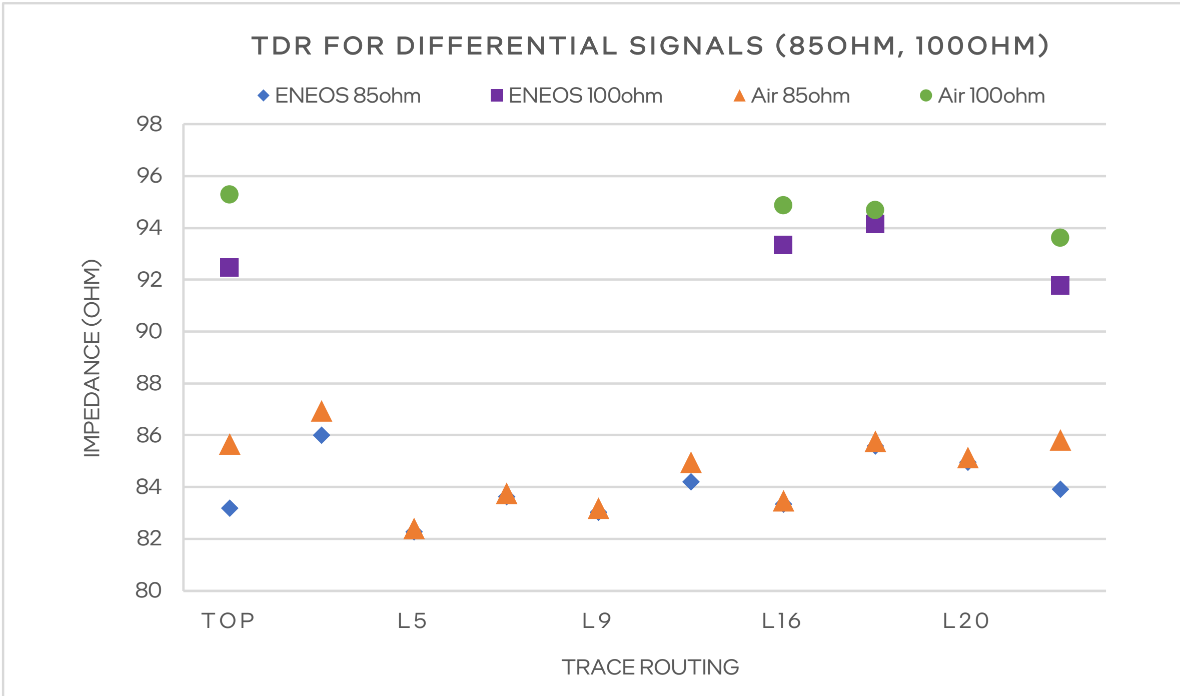
The test results show that the 4th Gen Intel® Xeon® Scalable processor-based 2U modular server used in these tests exhibited a junction temperature of 81° C when immersed, which complies with the Intel specification of up to 87° C.

(3) Server in Tank Signal Integrity

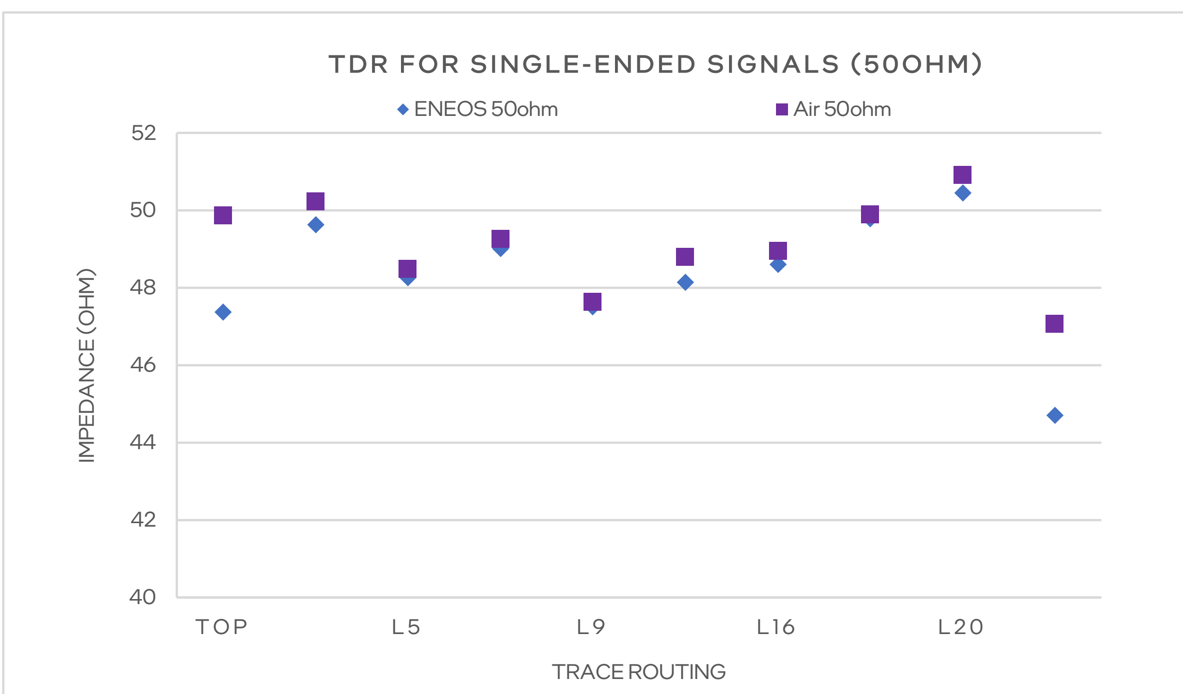
Comparing the server in tank signal integrity tests conducted within air cooling and with the testing done in the testing fluid:

- PCB stripline trace: No significant differences in impedance, loss, and far-end crosstalk (FEXT) and near-end crosstalk (NEXT).
- PCB microstrip (top and bottom) trace: The impedance is slightly lower, the loss is less, and FEXT and NEXT effects are slightly different than in air tests. Figures 6 and 7 show the PCB time domain reflectometer (TDR) and insertion loss test results.
- Connector and socket: The impedance is slightly lower, and the connector has more loss due to reflection than in air test, the loss of socket is close to in air test, and FEXT and NEXT effects don't have a significant impact on the channel performance.

Since the PCB microstrip, connectors and sockets are designed to be used in-air, it is recommended to take signal integrity in immersion as the main consideration for further design. We also highly recommend doing long-term reliability, availability and serviceability (RAS) tests to observe if there are any chemical changes that may cause the signal integrity issues after the system has spent a long period of time in the immersion tank.



A. TDR test for differential signals



B. TDR test for single-ended signals

Figure 6. PCB TDR test comparison

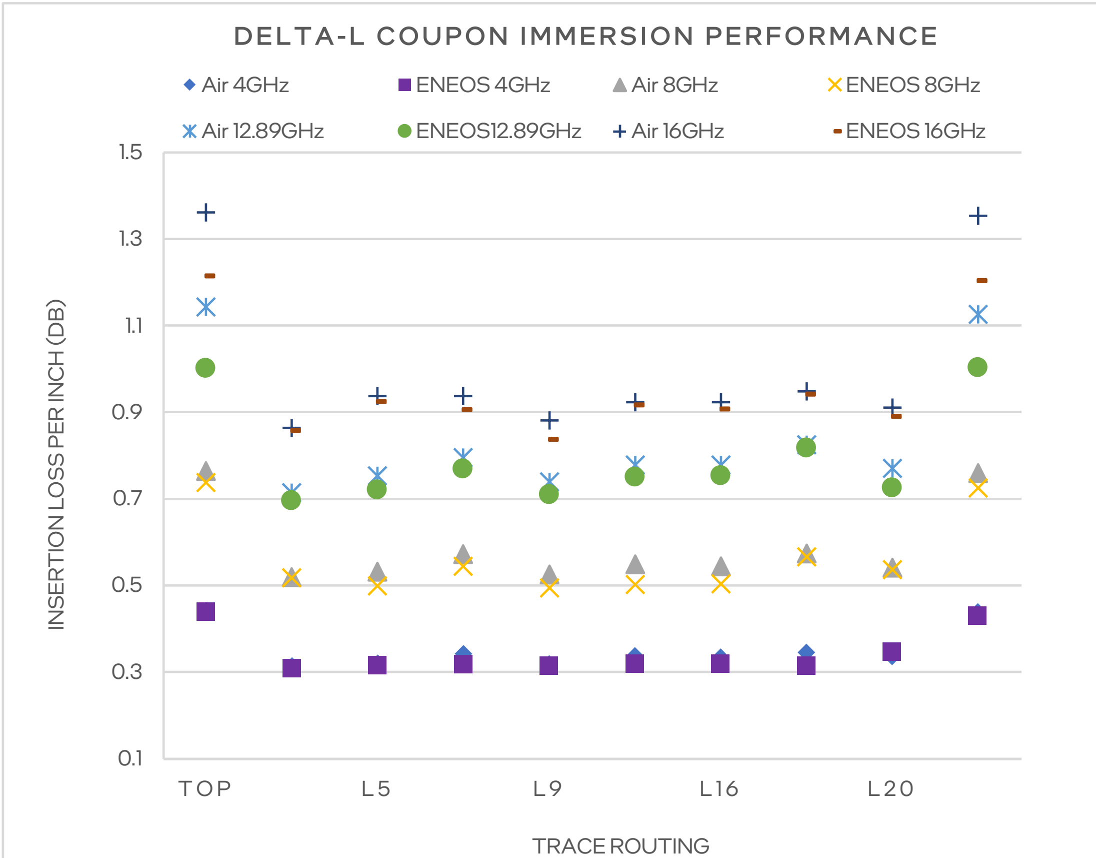


Figure 7. Insertion loss comparison

(4) Server in Tank Electrical Validation

Table 4 shows the IOMT test results. The IOMT results in air and in the testing fluid are slightly different on the average of lanes and follow Intel HSIO margin in-air guidelines.

CPU Margin Test				
2x10	DMI		PCIe Gen3	
	High/Low (V)	Right/Left (T)	High/Low (V)	Right/Left (T)
Mean_Air	120.4	18.53	100.98	16.98
Mean_ENEOS	117.32	17.26	97.8	15.96
Difference (Air-ENEOS)	3.08	1.27	3.18	1.02

PCH Margin Test				
2x10	USB3		PCIe Gen3/DMI Gen3/Uplink	
	High/Low (V)	Right/Left (T)	High/Low (V)	Right/Left (T)
Mean_Air	32.4	30.85	18.96	18.68
Mean_ENEOS	31.21	28.72	17.9	18.53
Difference (Air-ENEOS)	1.19	2.13	1.06	0.15

Table 4. IOMT test results

FileName	RxDqs-	RxDqs+	RxV-	RxV+	TxDq-	TxDq+	TxV-	TxV+	Ca-	Ca+	CaV-	CaV+	Cs-	Cs+
Mean_Air_4000	16.5	15.6	25.0	23.1	20.7	22.2	23.0	23.3	22.1	21.9	42.4	39.2	60.8	57.9
Mean_ENEOS_4000	16.0	15.4	24.8	23.0	20.6	22.1	23.0	23.2	21.8	21.2	41.8	38.7	60.4	57.8
Difference (Air - ENEOS)	0.5	0.2	0.2	0.1	0.1	0.1	0.0	0.1	0.3	0.7	0.7	0.6	0.3	0.1

Table 5. RMT test result

Table 5 shows the RMT test results, for the DDR5-4000 memory. Comparing the in-air results to the testing fluid RMT results, the differences are within 1 measurement point based on the average test results with whole channels. These differences may be caused by the deviation between boards and MRC re-training after each power-on. In conclusion, the testing fluid test result is low risk; however, we recommend conducting the long-term performance and reliability tests, like RAS, to assess the risk level.

(5) Optimal Server Heat Sink Verification

Server heat sink should be redesigned by CFD due to reduced flow velocity due to the changes in gravity and the viscosity in immersion cooling. Figure 8 shows the simulation results for immersion cooling heat sink design, the heat sink design parameters suitable for the testing fluid environment are fin pitch 3.5 mm and fin thickness 0.8 mm.

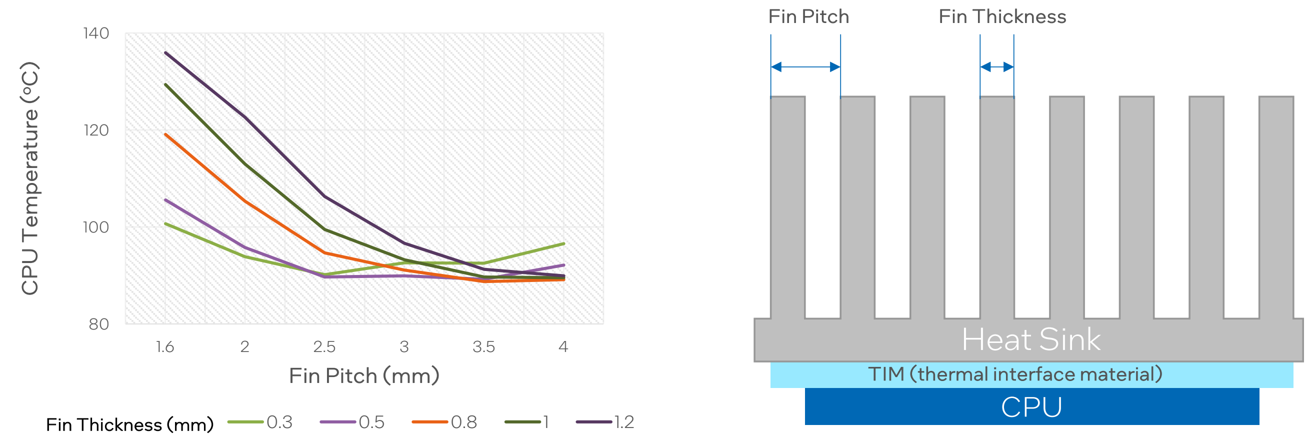


Figure 8. Simulation results for immersion cooling heat sink design

Figure 9 is the simulation comparison between the traditional air-cooled heat sink and the optimized heat sink in the immersion cooling system. From the results, it can be seen that the hot spots of air-cooled heat sink are more obvious, and the optimized immersion cooling heat sink is more uniform in temperature.

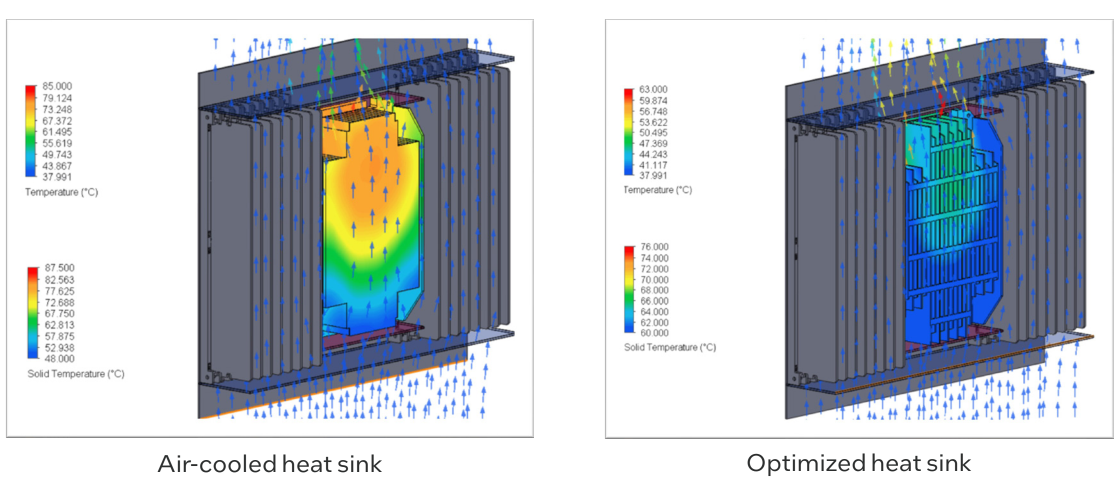


Figure 9. Simulation comparison results

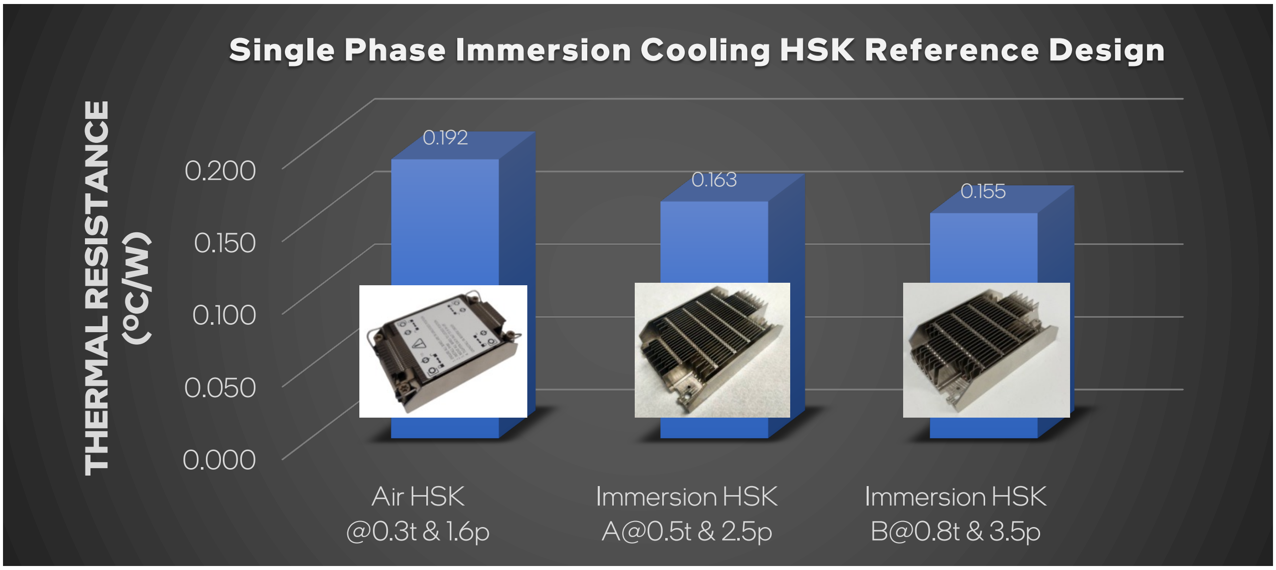


Figure 10. The results of heat sink verification

Figure 10 shows the actual test results. The thermal resistance value of the optimized immersion cooling heat sink is 0.155° C/W, which is better than that of the traditional air-cooled heat sink. The main reason is that the traditional air-cooled heat dissipation fins are relatively dense, which produces a large boundary layer and affects the heat dissipation efficiency. Another special feature of this design is that the unrestricted-fin design improves the heat exchange rate. Server heat sinks should be custom designed to work optimally for different coolants.

Coolant Test

(1) Coolant Specification

Coolant specifications, includes viscosity, density, dielectric constant, and other properties are shown in Table 6.

Property of Immersion Cooling Fluid

Sample Name			Immersion Cooling Fluid
Density	15 °C	g/cm^3	0.84
Flash Point	COC	°C	>250
Kinematic Viscosity	40 °C	mm^2/s	34.8
Specific Heat	25 °C	kJ/(kg ▪ K)	1.94
Thermal Conductivity	25 °C	W/(m ▪ K)	0.138
Rerative Dielectric Constant			2.14

Table 6. Immersion cooling fluid properties

Due to the Fire Service Act in Japan, immersion cooling fluids should have a flash point of 250°C or higher. There are two commonly used fluids: PAO8 is a fluid that can meet the flash point requirement, but its kinematic viscosity is too high consuming a lot of energy when circulating fluids in an immersion cooling system. PAO6 is a fluid with a lower viscosity than PAO8, which makes it difficult to guarantee the flash point requirement.

ENEOS has developed a new immersion cooling fluid (see Figure 11) that has a lower viscosity than PAO8 and a flash point of 250°C or higher using a highly refined base oil, effective for lowering failure rate of server components under long term use and increasing power efficiency. This new testing fluid also has excellent electrical insulation property. A conventional lubricant base oil has a slight yellow color, however the new testing fluid with highly refined base oil is colorless and transparent, increasing operational efficiency such as better visibility of server components under immersion cooling environment.

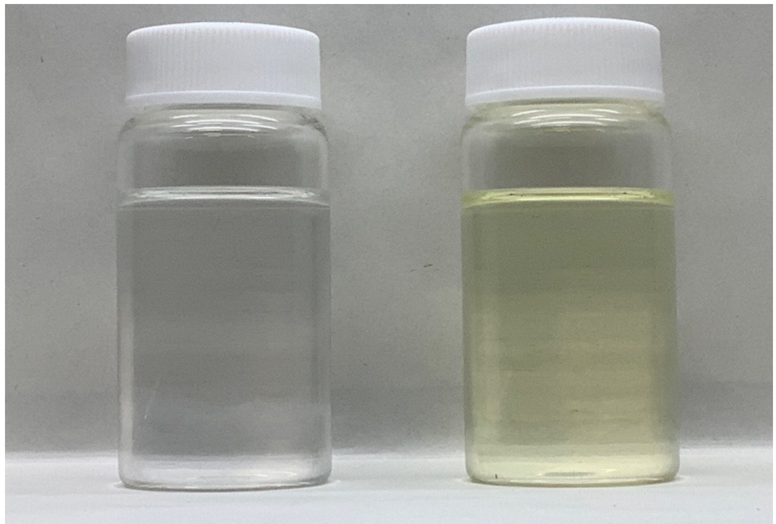


Figure 11. New ENEOS immersion cooling fluid (left) and general lubricant base oil (right)

The new fluid has adopted technology to provide excellent stability. From the results of accelerated tests conducted by ENEOS (see Figure 12), the new immersion cooling fluid has shown the ability to stay stable for up to 10 years, effective for long term use as minimal replacement of cooling fluid is required.

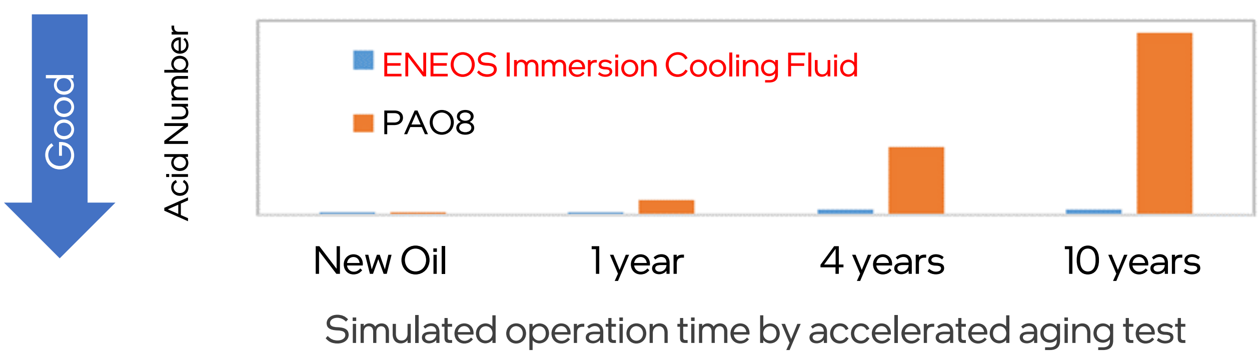


Figure 12. ENEOS immersion cooling fluid acceleration test result. Blue indicates ENEOS immersion cooling fluid and orange is general lubricant (lower is better)

(2) Material Compatibility Verification

Table 7 shows the results of the materials compatibility test. The test results confirmed that some materials are compatible and acceptable for immersion cooling environment, but still some materials such as glue, PVC and EPDM are incompatible with test coolant. These materials need to be replaced with others that are more suitable for immersion in a particular coolant.

In the material compatibility shown in Table 7, line 5 shows that two polyester fabric films were separated due to the dissolution of acrylic glue while in the immersion tank; thus, it is considered incompatible. Other incompatibilities are shown in items 14 and 19 where the remarkable swelling and weight gain was observed with each material. There was no significant change of the cooling fluid appearance after the tests using all materials.

Material Compatibility Test Results

No.	Material	Compatibility	Note
1	PBT+LCP+Gold & Tin plated terminal	Compatible	No remarkable change
2	PA66+Gold plated terminal	Compatible	No remarkable change
3	PCB FR4	Compatible	No remarkable change
4	PA66	Compatible	No remarkable change
5	Polyester Fabric & Acrylic Glue	Incompatible	Dissolution of glue
6	PET	Compatible	No remarkable change
7	Ethylene-vinyl acetate copolymer + flame retardant	Acceptable	Slight swelling
8	Teflon	Acceptable	Slight weight loss
9	Stainless steel	Compatible	No remarkable change
10	Nickel-plated stainless steel	Compatible	No remarkable change
11	Polyamide	Compatible	No remarkable change
12	PBT (halogenated)	Compatible	No remarkable change
13	PBT (Halogen Free)	Compatible	No remarkable change
14	PVC	Incompatible	Remarkable swelling
15	Gold plated terminal	Compatible	No remarkable change
16	Tin plated terminal	Compatible	No remarkable change
17	PVC+Cu	Compatible	No remarkable change
18	FKM	Compatible	No remarkable change
19	EPDM	Incompatible	Remarkable swelling

Table 7. The results of material compatibility verification[1]

The incompatible materials shown in Table 7 are usually used in the CPU's carrier power cable, PCIe riser power cable, and other power cables (see Figure 13). The tests help to avoid using incompatible material in the immersion cooling system.

Figure 13. CPU carrier power cable, PCIe riser power cable, power cable

Conclusion

The objective of PoC was to test Intel® Xeon® Scalable processor-based platforms' reliability in immersion systems, identify how the system and cooling fluids conditions change over time and to collaborate with ecosystem members – all of which was designed to expand the use of immersion cooling for commercial use.

The PoC verified the cooling capacity of the testing fluid and the thermal performance of the modular server. The PoC also demonstrated server in tank signal integrity and electrical validation. Lastly, the PoC showed some component material incompatibility which will factor into next-generation system design. Finally, the PoC helped to verify the design of the heat sink.

Based on the positive results of the PoC, Intel is planning to make progress on the immersion design guidelines for Intel® Xeon® Scalable processor-based servers. The company will expand the growing ecosystem members and customers to popularize the technology. Intel will also continue its material compatibility testing with a variety of different coolants and will help to define guidelines for warranties on Intel components and will also work with OEM ecosystem to define their warranty policy as necessary.

Through this successful PoC, KDDI has confirmed the effects of long-term use of server components and coolant under immersion cooling environment and also validated technical capability for commercial use. KDDI is aiming to integrate it into its data center operations in the near future.

KDDI, Intel and ecosystem members will continue to expand the ecosystem, always welcoming new partners with the same goal, to accelerate immersion cooling based solution in market.

Learn More

KDDI's Sustainability Efforts

Liquid Cooling of Servers in Data Center Achieves 94% Reduction in Cooling Power ~Realizing a Sustainable Immersion Cooling Data Center Contributing to Decarbonization, Commercialization in FY2023~ (March 6, 2023, Japanese)

Liquid Cooling of Servers Succeeds in Reducing Power Consumption by 43% in Containerized Data Center ~KDDI Oyama TC to Test Operation to Contribute to Decarbonization and Commercialization in FY2024~ (March 29, 2022, Japanese)

Intel and KDDI Sign Memorandum of Understanding to Reduce CO2 Emissions from Telecommunications Bureau Buildings ~First in Japan to control communication servers according to traffic, reducing power consumption by 20%~ (March 22, 2022, Japanese)

Sustainability Breakthrough with Immersion Cooling PoC at Small Data Centers ~Achieved PUE 1.07! Accelerate Verification of Sustainable Data Centers~ (January 19, 2022, Japanese)

ENEOS Corporate Website

Japan's Number One Lubricant Company Joins ElectroSafe Fluid Partner Program - Green Revolution Cooling (grcooling.com)

Intel Architecting the Sustainable Data Center with Intel's Open IP Immersion Cooling Modular Reference Solutions

Intel Makes Key Investments to Advance Data Center Sustainability (May 19, 2022)

Product Brief Intel's Open IP Immersion Cooling – Single Phase – 4U

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