Compact Thermal Management Solutions for High-Density AI Data Centers

OCP Educational Webinar Series

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Community-driven hyperscale innovation for all

Compact Thermal Management Solutions for High-Density AI Data Centers

James Kelly
VP Market Intelligence and Innovation

OPEN Compute Project®

Yulin Wang
Senior Technology Analyst

IDTechEx

Elvis Leka
New Product Development Engineer

Parker

Josh Coe
Market Manager

Parker

Agenda Overview

- Understanding Fluid Transfer Systems for Data Centers
- Efficiency Improvements
- Design Strategies
- Parker Products
- Key Takeaways
- Live Q&A

Agenda: Understanding Fluid Transfer Systems for Data Centers

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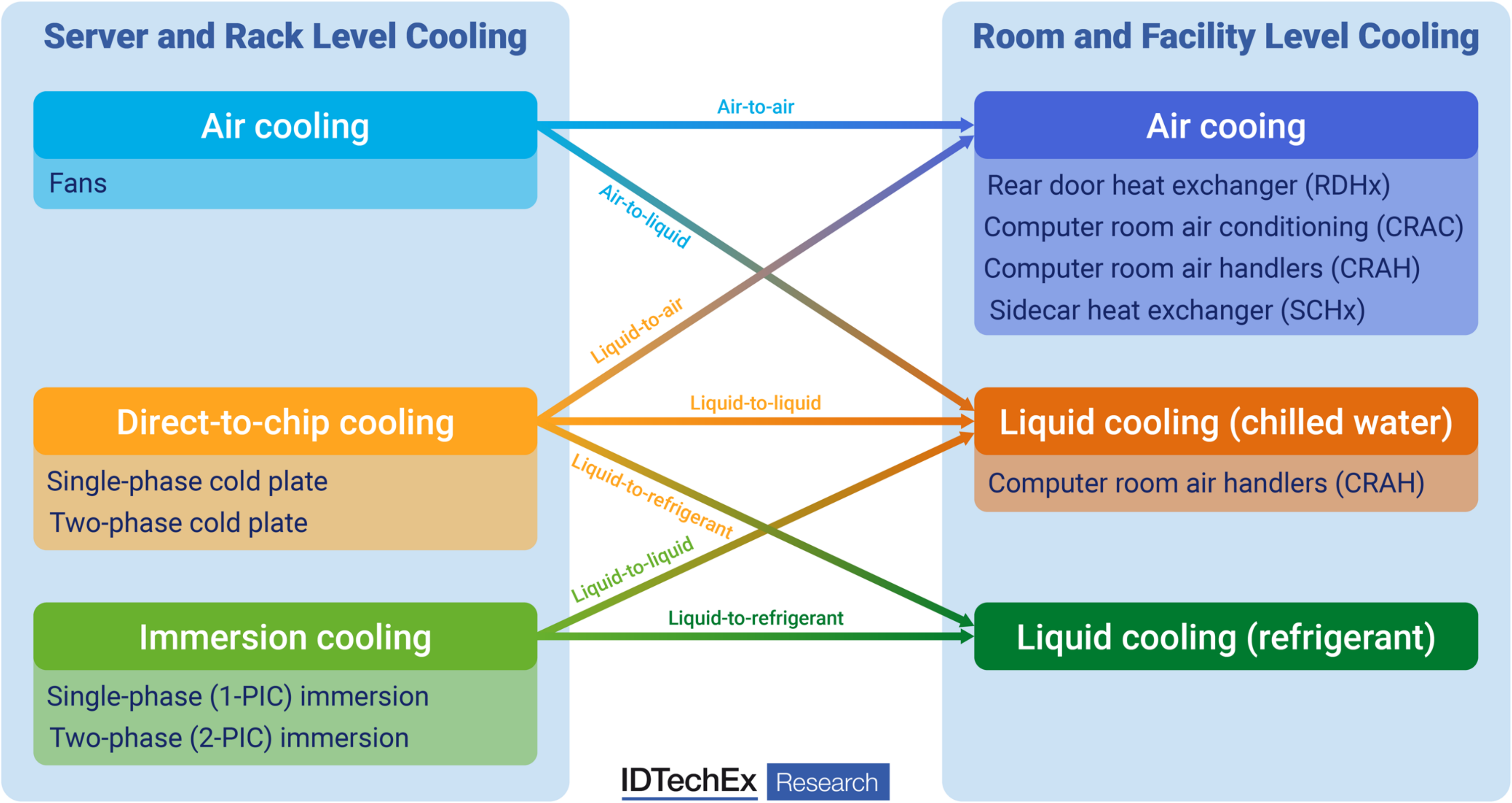
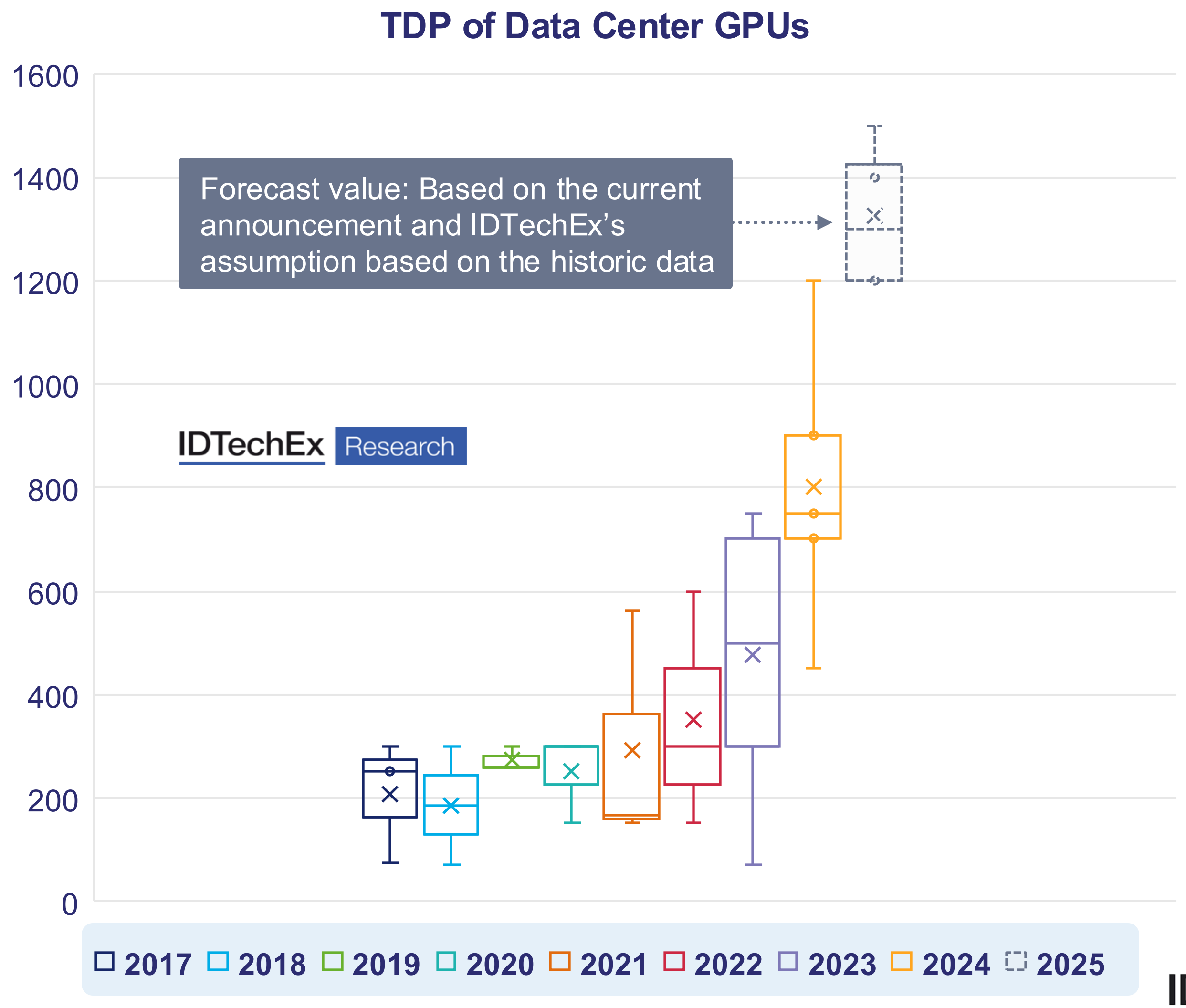
Data Center Cooling – Trends Towards Liquid Cooling



TDP Trend of GPUs

- **Thermal Management Challenges:** As GPU TDPs increase, advanced cooling solutions, such as liquid cooling, become essential to prevent overheating and maintain system efficiency.
- **Roadmap for two-phase cooling:** TDPs between 1500W and 2000W may mark the threshold where single-phase direct-to-chip (D2C) cooling no longer suffices, leading to the rise of two-phase cooling.
- **Implications for Data Centers:** Efficient heat dissipation is crucial for GPU performance and longevity, and higher TDPs complicate energy cost management, making thermal management a key focus in data center design. Due to the more complicated structure inside packaging, the tolerance to high junction temperature of silicon is lower, therefore requiring a better cooling.



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Single and Two-Phase Cold Plate: Challenges

Single-phase D2C

Technical challenges

- Leakage of coolant and risks on IT equipment – maintenance.
- Chaotic piping and hoses.
- Pumping, erosion corrosion, and high mechanical stress due to the high flow rate per minute.

Commercial challenges

- Complexity of plumbing due to the limited space and many cold plates – leading to replacement difficulty.
- Relatively high CAPEX due to retrofitting.
- IT and facility lifecycle mismatch.
- High maintenance over long time.

Two-phase D2C

Technical challenges

- Upfront system costs
- Managing flow and pressure across the cold plates
- Technician HVAC experience
- Health and environmental concerns: PFAS and GWP

Commercial challenges

- Complexity of initial system design
- High CAPEX (~20% higher for the cold plate system per unit, but the cost/watt is lower).
- Refrigerant supply

Single-phase D2C:

- Heat dissipation via convection
- Water glycol (e.g., 20% glycol and 80% water)
- High flow rate (e.g., 1.5L/min to cool down 1000W)
- Relatively high maintenance over time

Two-phase D2C:

- Heat dissipation via latent heat
- Dielectric fluids (e.g., Honeywell 1233zd and 515B), no damage to electronics in case of leak
- Low flow rate (0.3L/min to cool down 1000W)
- Relatively low maintenance over time

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Single and Two-Phase Immersion: Challenges

1-PIC immersion

Technical challenges

- Complexity of retrofitting and component-fluid compatibility test
- Coolant selection – a comprehensive material compatibility testing is needed
- Fluid disposal and lack of standardization

Commercial challenges

- Retrofitting complexity and risks of vendor locking in
- No clear standard on immersion cooling management
- Limited and complex warranty covering immersion-cooled servers

2-PIC immersion

Technical challenges

- All the technical challenges for 1-PIC
- Health and environmental concerns: PFAS and GWP
- Maintenance, additional retrofitting and infrastructure: sealing, filtration, and vapor toxicity

Commercial challenges

- All the challenges of 1-PIC
- Highest CAPEX out of the cooling solutions on this slide
- High coolant costs – 10 times+ more expensive than 1-PIC coolant
- Coolant vapor loss and toxicity

Single-phase immersion:

- Hydrocarbon oil typically (e.g., PAO oil)
- Cold plate + immersion (chassis-based immersion) emerging
- Coolant has a significant value

Two-phase immersion:

- Coolant: engineered fluids (7 times or more expensive than single-phase coolant)
- Leading immersion cooling vendors:
- Tanks: Iceotope, LiquidCool Solutions, GRC, Submer, Asperitas, etc.
- Coolant: Shell, BP, Castrol, Engineered Fluids, Honeywell, 3M, Chemours, SOLVAY, Total Energies, etc.

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Market Size and Commercial Trends

Total market size of liquid cooling to have a 3-fold increase by the end of this decade.

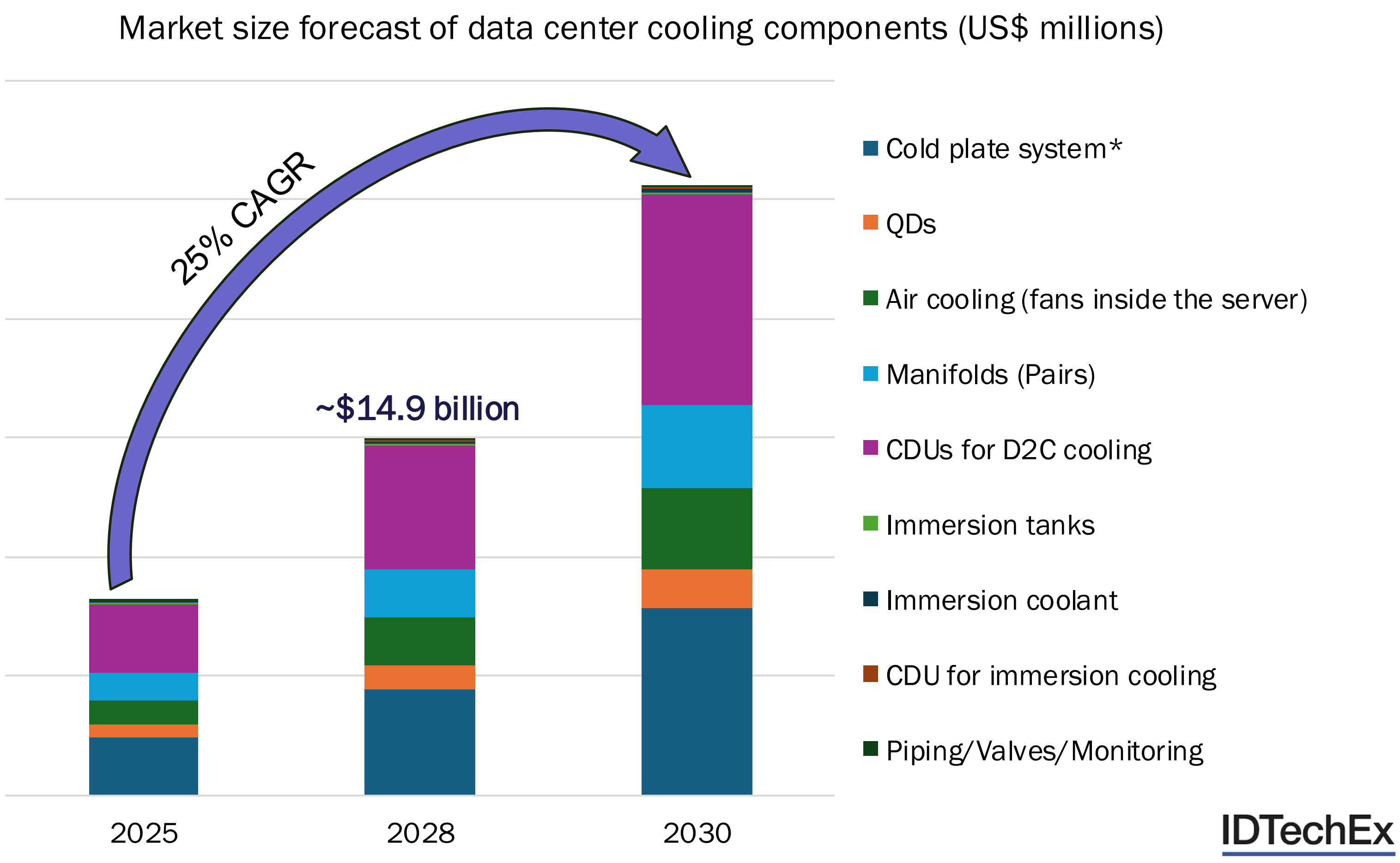
The report covers a granular market size forecast split by different component and AI/non-AI application.

AI drives the adoption of liquid cooling.

Two-phase D2C expected to take-off very soon.

Challenge – retrofitting and energy efficiency:

As liquid cooling adoption accelerates, retrofitting existing infrastructure poses a significant challenge, particularly in maintaining energy efficiency. Space-saving fluid transfer products become essential in optimizing thermal performance within constrained data center layouts.



** Cold plate system = cold plate + tubing + piping + fluid distribution manifold inside servers*

Audience Poll Question

What do you see as the timeline for significant adoption of single-phase liquid cooling?

- *A. Within the next 6 months*
- *B. 6 month to 2 years*
- *C. 2 – 5 years*
- *D. 5+ years*

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Overall Engineering Challenges

Increase Heat Density

Traditional cooling methods may become insufficient, leading to potential overheating and reduced reliability of hardware

Energy Efficiency

Engineers must design cooling solutions that minimize energy consumption while effectively managing heat

Space Constraints

Engineers need to optimize cooling systems to be compact and efficient, often leading to innovative designs like immersion cooling

Scalability

Engineers need to design flexible cooling solutions that can easily adapt to changing requirements without significant infrastructure changes

Reliability and Maintenance

Engineers must ensure that cooling systems are robust and easy to maintain, often requiring advanced monitoring and control systems

Interoperability

Engineers must ensure compatibility and seamless operation, which may require extensive testing and troubleshooting

Environmental Regulations

Engineers must innovate to comply with regulations while still providing effective cooling

Integration with Existing Systems

Engineers must find ways to integrate new cooling solutions with existing infrastructure, which can be complex and costly

Cost Constraints

Engineers need to balance performance, efficiency, and cost, often leading to compromises in design

Thermal Management Complexity

Engineers must develop sophisticated thermal management strategies to ensure uniform cooling across different types of hardware

Future Proofing

Engineers must design cooling systems that are adaptable to future advancements in computing technology, which requires foresight and innovation

Component Availability

Engineers rely on the timely availability of components and materials to meet project deadlines, which can impact cost as well

Energy Efficiency:
Power Usage Effectiveness

2007 Industry Average PUEs

2.5

Today Industry Average PUEs

1.55

1.3

Newer and Larger Facilities Average PUEs

Strategies to Minimize Thermal Management Loss:

- Optimize Cooling System (i.e. liquid cooling for superior thermal management)
- Utilize Energy-Efficient Hardware and Components
- Implement Effective Airflow Management
- Implement Real-Time Monitoring and Optimization

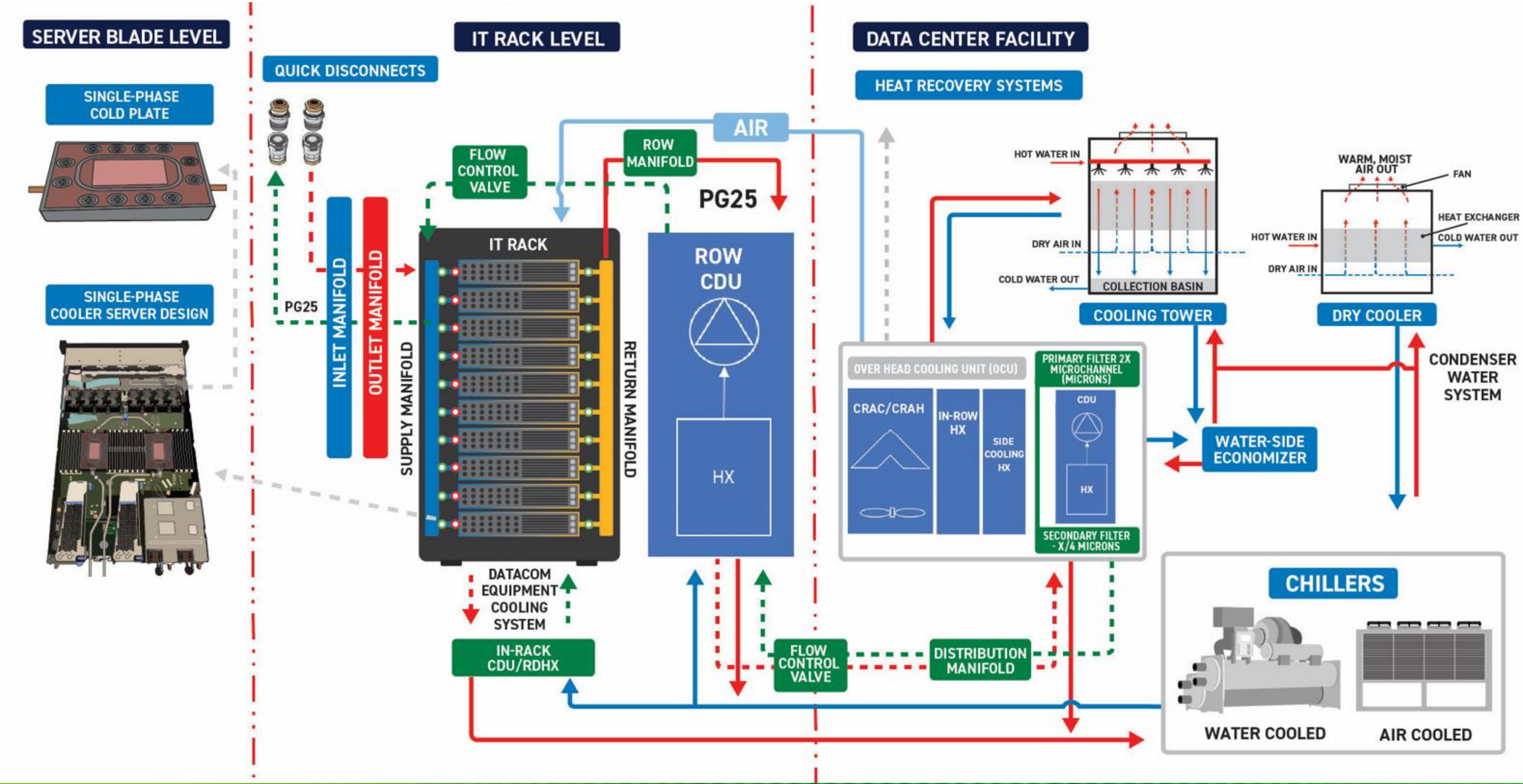
Thermal management loss stems primarily from inefficiencies in heat dissipation, leading to energy waste and potential hardware damage

Benefits of Enhanced Thermal Management:

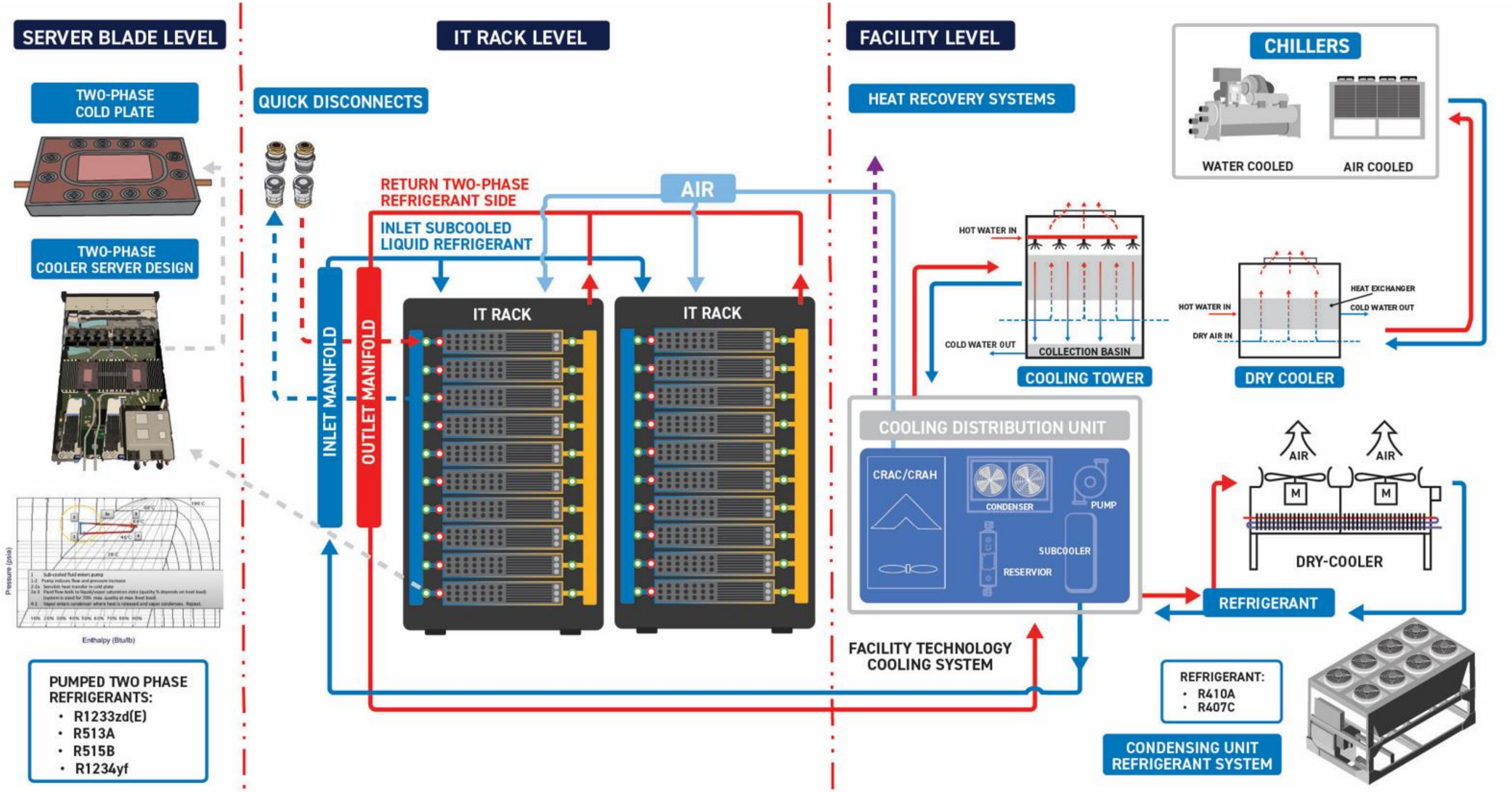
- Extended Equipment Lifespan
- Improved Operational Efficiency
- Increased Performance
- Reduced Carbon Footprint

While Power Usage Effectiveness (PUE) measures the overall energy efficiency of a data center, it's important to focus on improving the efficiency of IT equipment as well

Single-Phase Liquid Cooling

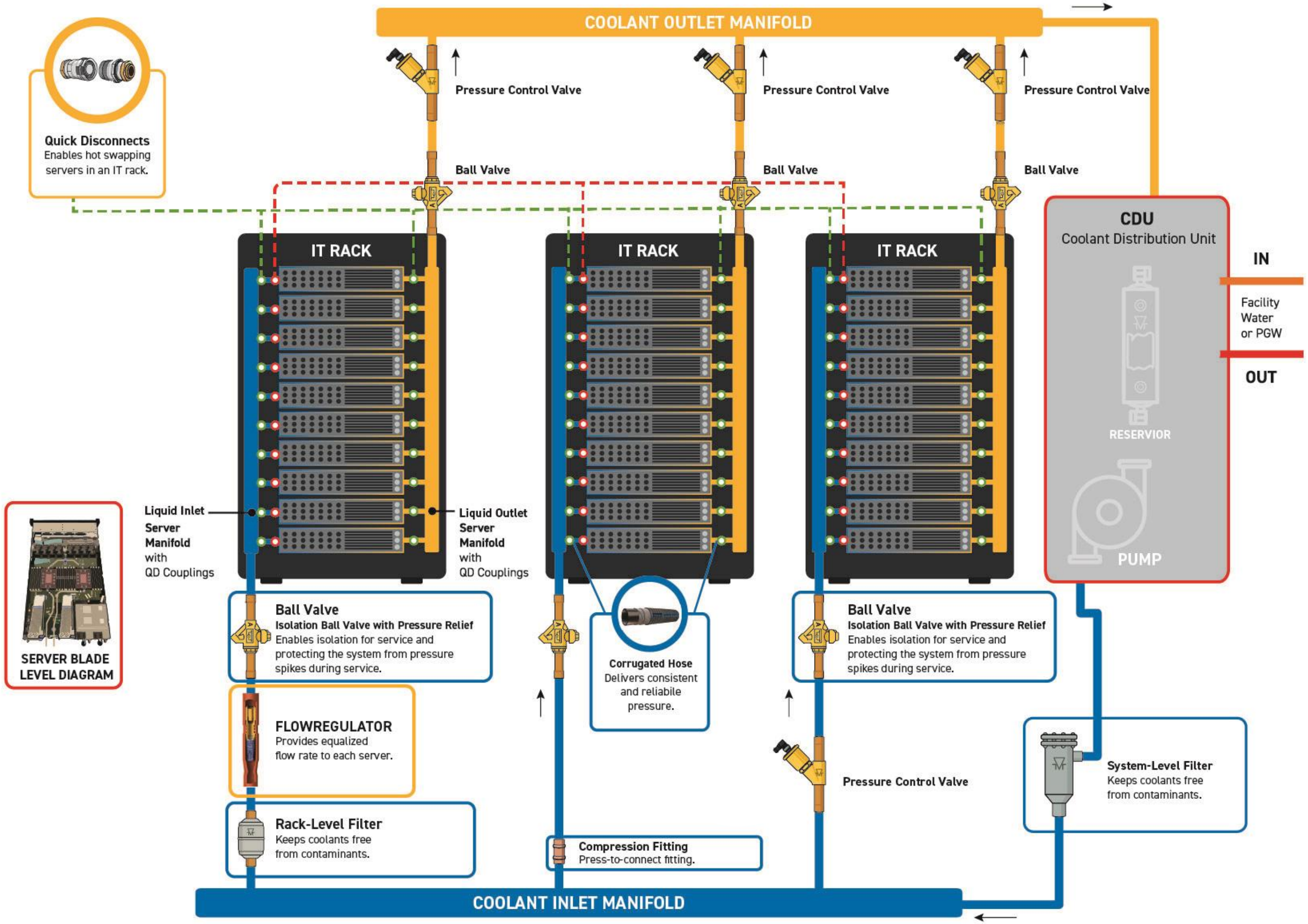


Two-Phase Liquid Cooling



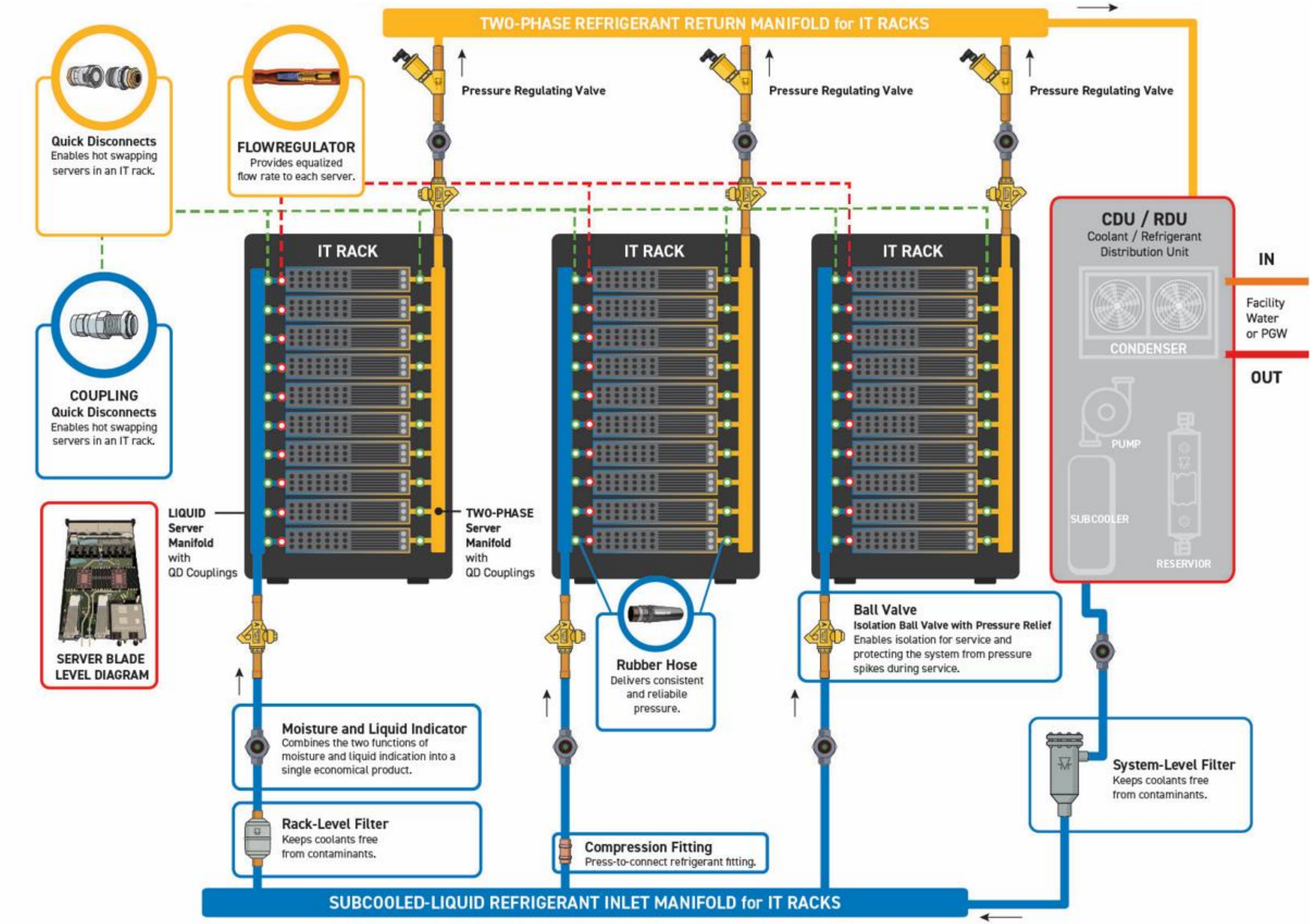
Data Center Cooling Piping Diagram

Single-Phase Direct-to-Chip Liquid Cooling

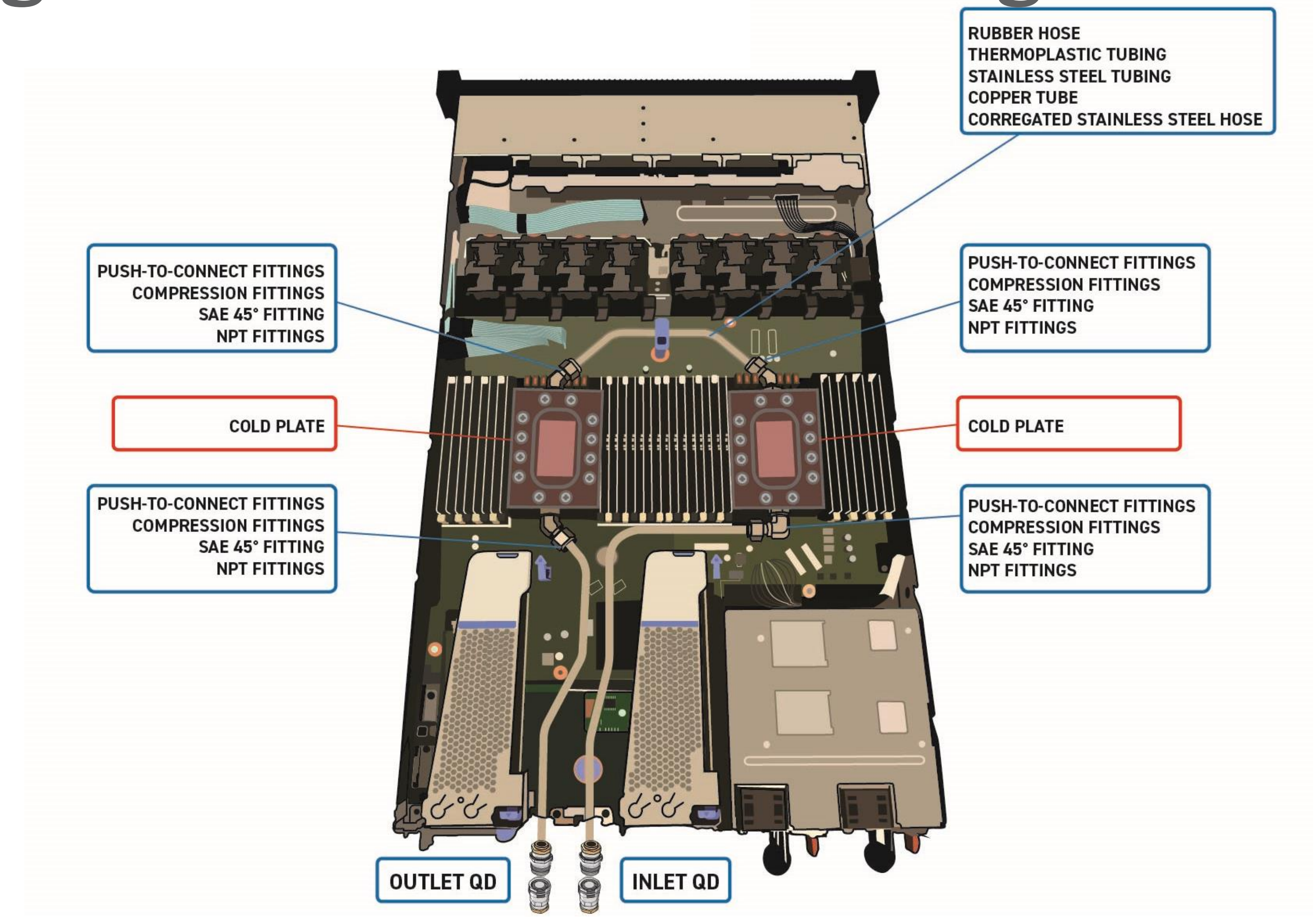


Data Center Cooling Piping Diagram

Two-Phase Direct-to-Chip Liquid Cooling



Single-Phase Server Blade Diagram



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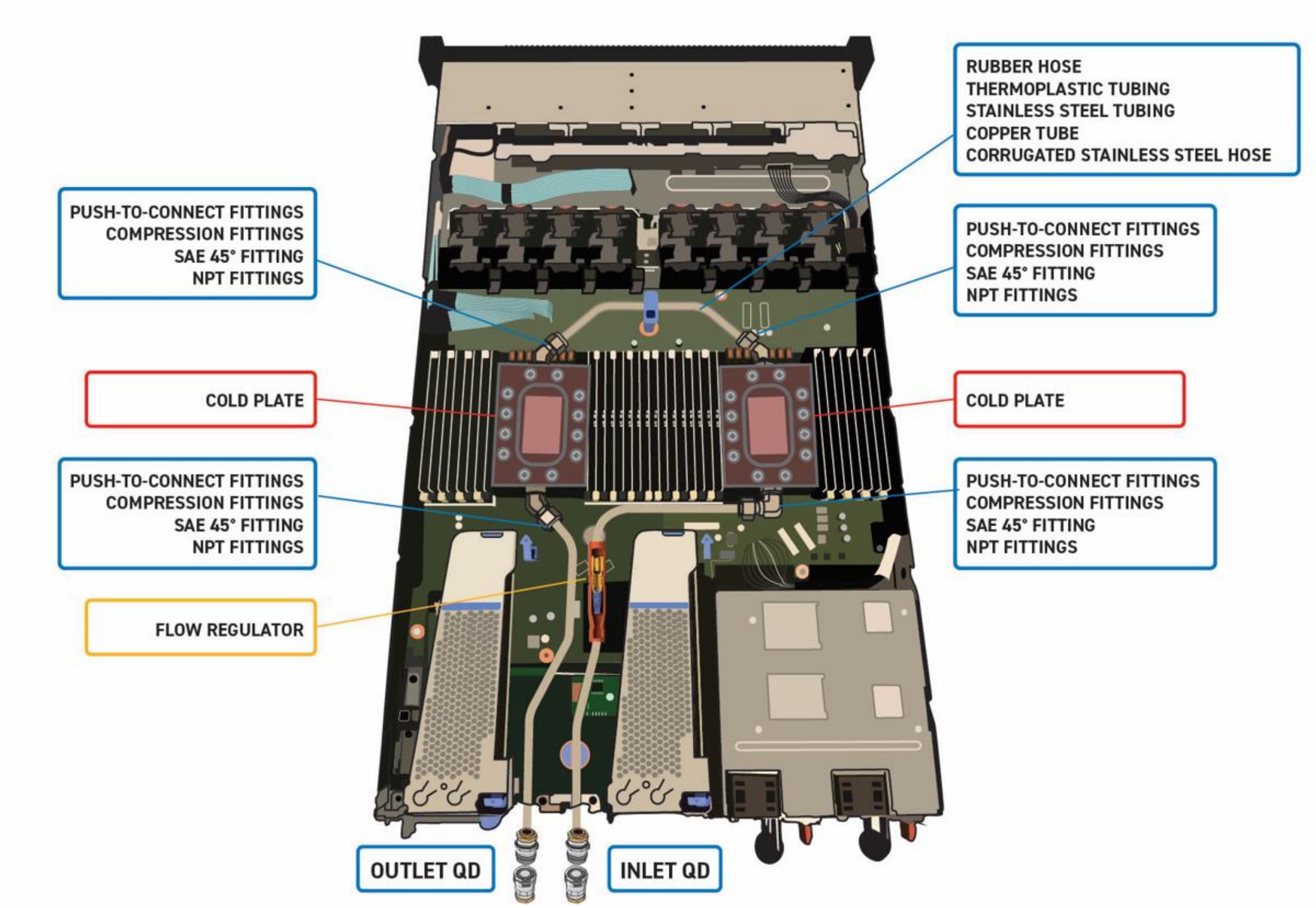
Two-Phase Server Blade Diagram



Energy Efficiency: Pressure Drop Minimization

Pressure drop refers to the reduction in pressure as coolant flows through a system, impacting the efficiency of thermal management. Minimizing pressure drop is crucial for ensuring optimal coolant flow, enhancing cooling efficiency, and reducing energy consumption.

Sources of Pressure Drop

Strategies for Minimization

Benefits of Low Pressure Drop

Effective pressure drop minimization is essential for the reliable and efficient operation of thermal management systems in data centers, contributing to better performance and sustainability

Energy Efficiency: Pressure Drop Simulation

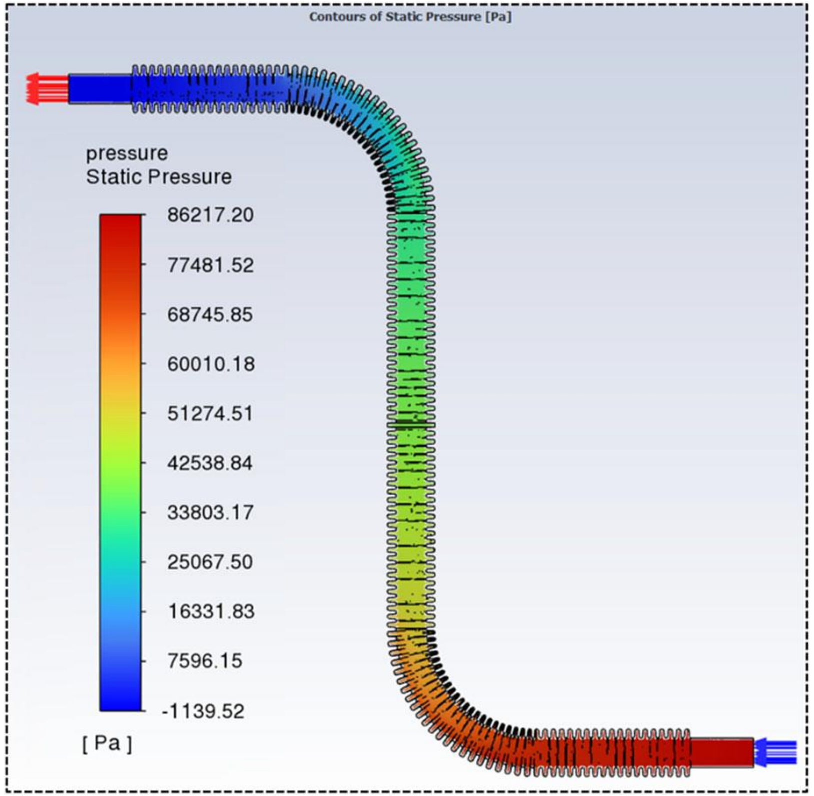
Materials:

- 12mm OD x 6.5mm ID hose with fitting (0.155" Ø)
- 10mm OD x 6.5mm ID corrugated ss steel tube
- 12mm OD x 9.5mm ID thermoplastic tube
- 10mm OD x 8mm ID thermoplastic tube

Parameters:

- DOWFROST PG30 @ 40C
- Flow rates: 1 and 5 liters per minute
- 300mm sample length
- S shape routing

Flow Rate Liters per Minute	12mm X 6.5mm Rubber Hose	10mm X 6.5mm Corrugated SS	12mm X 9.5mm TP Tube	10mm X 8mm TP Tube
1 lpm	0.268 psi	0.12 psi	0.019 psi	0.030 psi
5 lpm	4.21 psi	2.82 psi	0.251 psi	0.410 psi



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Space Constraints

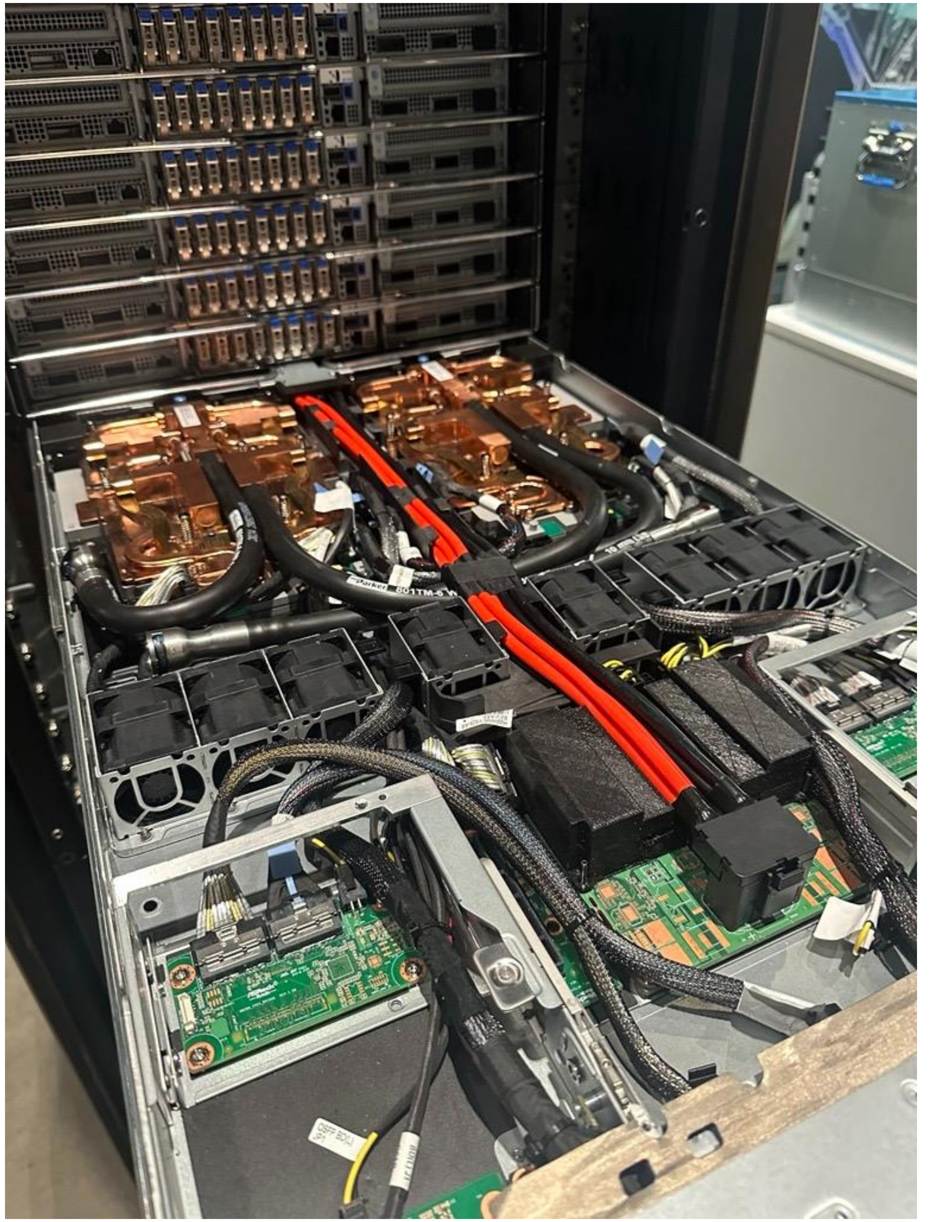
1 Component Size Configurations

2 Difficulty Implementing Efficient Cooling Designs

3 Concentrated Heat Loads (High Density)

4 Maintenance and Access Issues

5 Cable Management Conflicts



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Liquid Cooling: Reliability and Maintenance

Reliability Challenges

- High Component Stress and Density
- Complexity and Interdependence
- Single Point of Failure
- Component Compatibility

Maintenance Challenges

- Limited Access and High Density
- Need for Continuous Operations
- Specialized Skills and Diagnostics
- Preventative Maintenance Complexity
- Integration with Legacy Systems

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Design Strategies – Hose and Tubing

Things to Consider When Specifying:

Sizing Considerations
Ensures optimal flow, reduces pressure drop and wear, ID affects flow, OD affects routing and installation

Force to Bend
Bending force impacts installation and performance, it must stay within specs to prevent kinking or damage

Bend Radius
The minimum radius to which a hose can be bent without compromising its integrity and it is highly recommended to follow manufacturer guidelines for bend radius to maintain flow efficiency and prevent leaks

Compatibility
Ensure hose materials are compatible with the coolant and withstand temperature, pressure, and chemical exposure, confirmed through proper testing

End Connections

- Threaded: Secure, may need sealants
- Quick Disconnects: Easy maintenance
- Barbed Fittings: Simple, clamp recommended
- Push-Lok: Leak-free with matching hose
- Push-In: Tool-free, quick, for low pressure

Sealing

- O-rings: For threaded, ensure fit & compatibility
- Gaskets: For flanged connections
- Sealants: Enhance threaded seals

Design Strategies – Quick Disconnects

Things to Consider When Specifying:

Pressure Drop vs Flow Rate
Quick disconnects can introduce pressure drops in the system, affecting overall flow rates

Compatibility & Testing Requirements
Ensure all component materials are compatible with coolant and conduct tests to prevent failure

Corrosion
Use corrosion-resistant materials (e.g., stainless steel, brass, or specialized plastics) to enhance longevity

Ease of Use
Quick disconnects are designed for easy operation, allowing for fast coupling & uncoupling without tools

End Connection Types
Quick disconnects can be paired with various end connections, such as barbed, threaded, or push-in fittings

- Push-to-Connect: Very quick and easy, low pressure
- Threaded Disconnect: Secure connection, higher pressure
- Bayonet Style: Quick twist-lock, moderate pressure
- Cam-and-Groove Style: Very fast with good sealing

Design Strategies – Fittings

Things to Consider When Specifying:

Flow vs Compactness Requirements
Having the highest flow in limited space is an engineering trade-off that can be addressed with fitting technologies

Leak Prevention & Reliability
Fittings and tubing technologies must be specified together to ensure the system robustness and reliability

Ease of Installation & Connection
Design of the fitting can save significant assembly time & ease tubing or hoses assembly

Compatibility & Testing Requirements
Ensure materials are compatible with coolant and conduct tests to prevent failure

End Connections & Shapes
Fittings have wide ranges of terminations and shapes that can support almost all liquid cooling system design

Design Strategies – Valves

Things to Consider When Specifying:

Leak Tightness and Reliability
Valves must provide a reliable seal to prevent leaks under operating pressures and temperatures, proven sealing technologies and rated for continuous operation

Compatibility with Coolant and Materials
Valve materials (body, seals, seats) must be compatible with the chosen coolant (e.g., water, glycol mixtures) to avoid corrosion, swelling, or degradation

Ease of Operation and Maintenance
Valves should be easy to operate (manual or automated) and accessible within the rack for quick shutoff or flow control

Flow and Pressure Requirements
Valves must support the required flow rates without excessive pressure drop - consider valves that allow fine flow regulation if needed

Design Strategies – Manifolds

Things to Consider When Specifying:

Compatibility
Requires selecting materials that withstand coolant and operating conditions and integrate smoothly with existing system parts for reliable performance

Size for Flow Requirement
Make selection based on the required flow rates to ensure adequate coolant distribution to all components and design for future expansions or modifications to the cooling system

End Connections
Select appropriate end connections based on application requirements and ease of installation and are compatible with hoses, tubing and other components

Ease of Use
Position in accessible locations to facilitate routine maintenance, inspections, repairs and easy replacement or modifications of sections without disruption

Design Strategies - Medias

PG25 (Propylene Glycol 25%):
A non-toxic antifreeze solution commonly used in cooling systems that provides good thermal conductivity and low freezing point

- Concentration Management
- Compatibility Testing
- Monitoring

Water:
Excellent thermal conductivity and heat capacity; widely used due to its availability and cost-effectiveness

- Water Quality Management
- Corrosion Inhibitors
- Temperature Control

Inhibitors:
Chemical additives used to prevent corrosion, scale formation, and biological growth in cooling systems

- Selection of Inhibitors
- Regular Monitoring
- Environmental Considerations

Refrigerants:
Fluids used in cooling systems that undergo phase changes to absorb and release heat (e.g., R-134a)

- Selection of Refrigerants
- System Design Considerations
- Leak Detection

Additional Component Design Considerations

Pumps

- **Flow Rate:** Match cooling system requirements
- **Pressure:** Overcome system resistance
- **Energy Efficiency**: Use high-efficiency pumps with VFDs
- **Reliability:** Durable, maintainable, with available spare parts
- **Material Compatibility:** Suitable for coolant type
- **Proper Sizing:** Avoid oversizing to save energy and protect pump

Cold Plate

- **Thermal Performance:** Efficient heat removal
- **Flow Design:** Maximize transfer, minimize pressure drop
- **Material:** High conductivity and corrosion-resistant
- **Size/Form Factor:** Fits space and layout
- **Coolant Compatibility:** Matches coolant type
- **Burst Pressure:** Withstands system pressure safely
- **Cost & Manufacturability:** Balance performance and cost
- **Reliability:** Durable under thermal cycling

Real-World Case Studies

Hose and Tubing Optimization in a Hyperscaler

- **Overview:** A hyperscaler sought to improve its liquid cooling system by optimizing the hose and tubing configurations to reduce overall system pressure drop and enhance overall cooling performance.
- **Initial Challenge:** The hyperscaler experienced significant pressure losses in its liquid cooling system due to the use of non-optimized hose sizes, routing, and configurations.
- **Optimization Strategy:** The company optimized hose diameters, with larger bore diameters, flexible tubing, and appropriate hose offerings designed for low-pressure drop. Further, routings were altered to reduce sharp bends.
- **Results:** The optimization reduced the pressure drop, resulting in a significant increase in coolant flow rate, improved heat transfer, and a reduction in overall energy consumption for the cooling system.

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Real-World Case Studies

Optimization of Quick Connect Fittings in a Data Center Cooling System

- **Overview:** A leading data center operator aimed to enhance the efficiency and reliability of its liquid cooling system by optimizing the quick connect fittings used for connecting hoses and tubing, which are essential for maintenance and system scalability.

- **Initial Challenge:** The existing quick connect fittings were prone to leaks and pressure drops, causing operational inefficiencies during maintenance and leading to inconsistent coolant flow. The system experienced an average pressure drop of 6 psi due to poor sealing and flow resistance, negatively impacting cooling performance and increasing operational costs.

- **Optimization Strategy:** The engineering team evaluated multiple quick connect fittings, selecting high-performance, advanced-material designs with superior sealing and reduced flow resistance. They standardized fitting sizes across cooling units for compatibility and implemented thorough testing to ensure performance under varied conditions.

- **Results:** The new quick connect fitting system reduced the pressure drop to 2 psi, significantly improving the overall coolant flow rate. Enhanced sealing properties minimized leaks, which decreased maintenance downtime by 30%. The improved reliability of the connections led to a 15% reduction in overall cooling system energy consumption, contributing to both operational efficiency and cost savings.

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SP2P Tubing

Parker's Parflex SP2P tubing is a thermally formable, thin-wall tubing designed for single and two-phase data center cooling, offering ultra-low pressure drop, easy installation, and minimal permeation with standard refrigerants. SP2P has a UL94 VO rated thermoplastic elastomer cover.

- Ultra-low permeation chemically resistant polyamide liner (<1.4kg/m^2/yr)
- Available in metric sizes
- Designed to maximize coolant flow and minimize pressure loss
- Can be thermally formed for repeatable precise routings

Pure Coolant Tubing

Parker's Parflex Pure Coolant Tubing (PCT) is a type of multi-layer Polyamyde tubing that is designed for data center applications requiring reliable ultra-low pressure drop, ease of installation, as well as excellent chemical compatibility.

- UL94 VO rated product
- Available in PFA and PA materials
- Available in metric sizes to match Parker's Carstick metric offerings
- Designed to maximize coolant flow and minimize pressure loss
- Can be thermally formed for repeatable precise routings

https://www.parker.com/data-center

Peroxide Cured EPDM Hoses

These Parker hoses leverage the inherent benefits of EPDM (coolant/water/heat/ozone resistance) and enhance them, particularly regarding high-temperature performance and longevity, through the use of a peroxide cure system.UL94 VO rated thermoplastic elastomer cover.

- 627 Thermal Cooling Hose
- 629 Server Blade Hose
- 807 Push-Lok Hose
- 7395 E-Z Form GS Hose

Customized Manifold Solutions

Parker's customized in-rack manifold solutions are designed to distribute even amounts of fluid to each individual cold plate so you can maximize the output of your high-performance computing system.

- Available in various materials to eliminate compatibility concerns
- Flow distribution simulations to support dimensioning and design
- Leak-tested assemblies
- Enhanced system reliability
- Optimized fluid usage
- Improved serviceability

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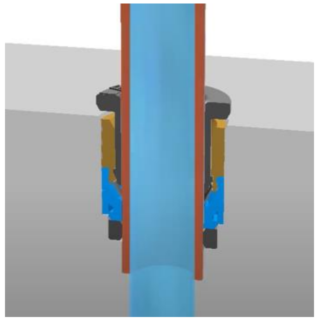
Liquid Cooling Cartridge (Carstick®)

Carstick is a fully assembled and integrated cartridge providing instant connection between the housing and the tubing. It can be inserted into cavities made of a wide range of materials. This is the right connection solution for energy, space and time saving.

- Single component product for reduced insertion time 2 to 3 times faster than standard cartridge solutions
- The most compact cartridge on the market
- Economical alternative to threaded connectors
- Only the seal is in contact with the conveyed fluid
- High burst and leak performance



Quick Disconnect Couplings

Parker's Universal Quick Disconnect (UQD) is an OCP Inspired™ product based on the approved OCP UQD specification v1.0. Available in handmate and blindmate connection style from –02 to –08 sizes.

- Flush-face valve design prevents fluid loss and optimum protection of electrical components
- Reduced pressure drop for superior energy efficiency and system performance
- Suited for cold plate, manifold and CDU applications
- Available in threaded and hose barb port terminations as well as red and blue for hand mate couplings

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Push-Button Universal Quick Disconnect

Parker's push-button UQD is a non-spill disconnect solution for liquid cooling systems in data centers and supercomputers that meets OCP specifications. The innovative combination of high-performance polymer and metal offers superior flow rate, high mechanical performances and flammability regulation compliance.

- Easy to handle & operate
- No spillage during connection/disconnection
- High flow design
- Robust hybrid high performance polymer and stainless-steel design
- Compact and lightweight

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Sporlan Dry Break Coupling (QTQD)

Parker's Sporlan QTQD is a dry break coupling designed specifically for 2 phase cooling in data centers. The design builds from Sporlan's couplings that have been produced for decades.

- Rated for R1233zd(e) and R515B
- Quickly connect by hand or with wrenches
- Threads in 2-3 turns
- Multiple sizes available
- Multiple adapters available (O-ring Boss, Hose Barb)
- Connect/Disconnect at over 200 psi pressure

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Optimizing Thermal Management for Next-Gen Data Centers

Energy Efficiency	PUE plateau (~1.55); newer sites achieve ≤1.3.
	Enhanced thermal strategies reduce energy waste & extend hardware life.
	Pressure drop minimization critical: optimized tubing, fittings, and manifold design lead to lower pump energy.
Flow Management Optimization	Smart component selection (e.g., low-resistance tubing, UQD fittings) cuts system pressure drop by up to 85%.
	Simulation-guided design prevents turbulent flow, improves cooling reliability, and simplifies retrofitting.
Cooling Efficiency & Energy Costs	Transition from air → liquid → two-phase cooling to manage rising GPU TDPs (up to 2000W).
	Two-phase direct-to-chip cooling reduces flow rate needs by 80%, with lower maintenance and better thermal control.
Technology Trends & Future-Proofing	AI-driven dynamic cooling and pressure monitoring expected to rise.
	Two-phase and refrigerant-based systems gaining traction despite higher CAPEX – for hyperscale adoption.
	By 2030, liquid cooling component market projected to triple, driven by AI workloads and retrofitting needs.

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