WHITEPAPER

DIRECT LIQUID COOLING OPTIMIZATION

The Containment Advantage

By Gordon Johnson

The rapid growth of AI workloads and servers are pushing rack densities up to and beyond 100 kW per rack with no end in sight. Traditional cooling methods such as raised-floor perimeter cooling are approaching their practical limits in terms of feasibility and efficiency. With rising chip and rack densities, most people agree that the future of data center cooling is moving from a room-based cooling design to direct heat removal at the server and especially at the processor level, also known as Direct Liquid Cooling (DLC).

Introduction

Hybrid cooling is increasingly recognized as the way to future-proof the data center investment. It's ideal for legacy retrofits since it allows the facility to gradually transition toward more advanced cooling methods as needed. It's also become the cooling technology method of choice for new and future data centers that are prioritizing long-term growth and sustainable goals.

With hybrid cooling shaping the path forward, it's reasonable to question whether containment still matters in modern data center and cooling designs. This white paper explains why containment remains the essential, non-negotiable requirement in a data center's thermal management architecture, regardless of which cooling technologies are deployed.

This paper will also discuss the following:

1. Drivers Behind Liquid Cooling Adoption
2. Core Components of Hybrid Cooling
3. DLC Technologies: Current Leaders and Future Front-Runners
4. Containment: The Non-Negotiable Infrastructure
5. Containment: The Fastest Path to Thermal Reliability and Efficiency
6. Next-Generation Products for Efficient and Sustainable HPC

Drivers Behind Liquid Cooling Adoption

What's driving the shift toward liquid cooling? Processor technology has reached a point where meaningful performance gains require substantially higher power densities, and that power translates directly into heat. Modern CPUs, GPUs, and AI accelerators now operate at thermal loads that exceed the practical limits of air cooling. At the same time, AI and High-Performance Computing (HPC) are reshaping data center architectures, pushing rack densities far beyond the ~25-35 kW range where traditional air cooling becomes inefficient and increasingly unsustainable. With racks approaching and now exceeding 100 kW, liquid cooling is rapidly becoming the only scalable path forward for next-generation compute.

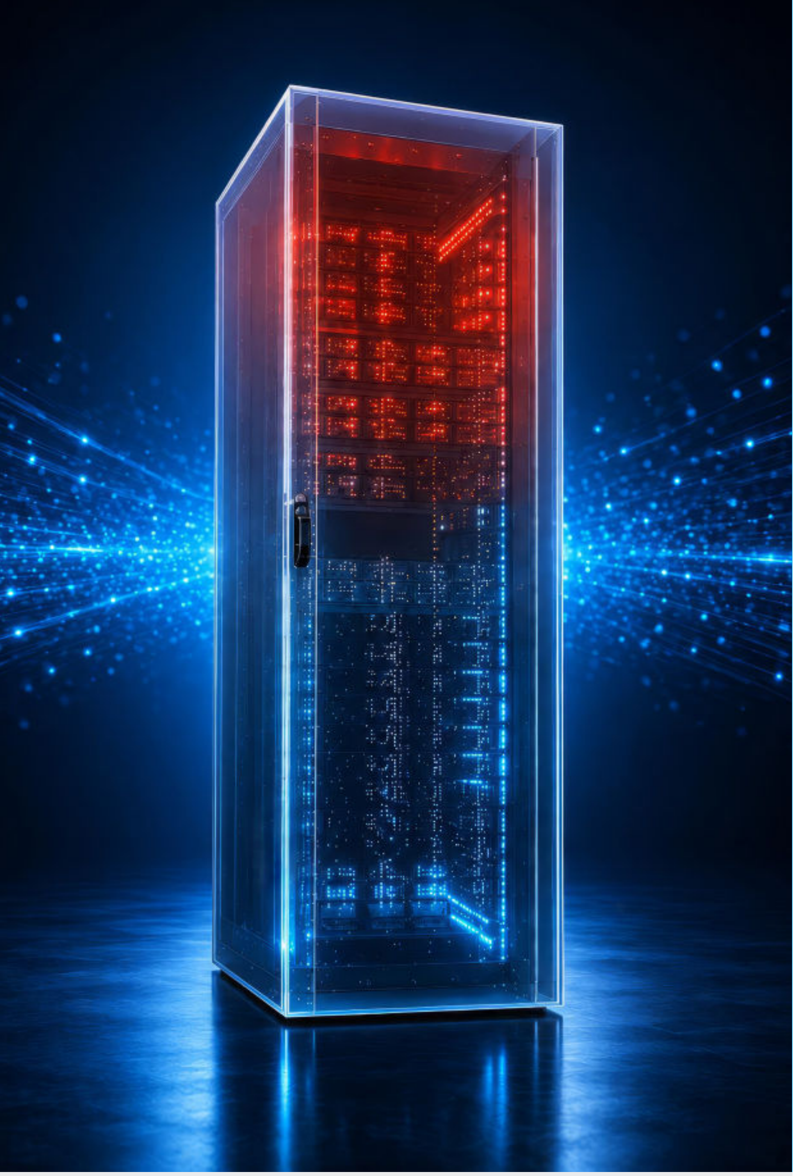
Liquid cooling, which has been around for decades, is fundamentally more efficient than air because of its higher density, specific heat capacity, and lower thermal resistance. Water can absorb or hold over 3,000 times more heat per unit volume than air (thermal capacity), enabling far more effective heat transfer from a processor using a significantly smaller volume of coolant compared to the air volume required for similar air cooling.

Water also conducts heat far more effectively than air, with over 23 times higher thermal conductivity. To illustrate, consider a simple scenario: placing a burned fingertip in 50 °F (10 °C) water removes heat and relieves pain far more rapidly than exposing it to 32 °F (0 °C) air. Despite the water being warmer, its much higher thermal conductivity allows it to draw heat away from the skin far more efficiently. The same principle applies in data center cooling. Liquids transfer thermal energy orders of magnitude faster than air, enabling stable, high-density heat removal.

The efficiency of liquid cooling at high-power densities delivers measurable operational advantages including higher sustained processor performance, increased economization hours, and new opportunities for waste-heat recovery.

Core Components of Hybrid Cooling

Hybrid cooling integrates air and liquid cooling technologies to manage the heat generated by low-density and high-density compute loads. This approach provides a scalable transition path that improves thermal efficiency, performance stability, and cost control as data center workloads intensify, particularly with the rapid expansion of AI-driven HPC systems.



Hybrid cooling uses air cooling for lower-density or legacy IT equipment, while liquid cooling, typically Direct-to-Chip (DTC), targets high-heat components such as CPUs, GPUs, and AI accelerators. Because DTC removes only a portion of the total rack heat load, air cooling remains essential for extracting the ~25% residual thermal energy. Both cooling methods operate concurrently and rely on cold aisle or hot aisle containment to maintain separation between supply and exhaust air streams and ensure stable thermal performance across the data hall. Without containment, hybrid cooling systems experience excess bypass airflow, net recirculation airflow, and unstable server inlet temperatures.

Hybrid cooling can also be deployed using a zoned approach, applying DLC to high-density racks while continuing to use air cooling for lower-density racks, with each located in separate areas or zones within the data hall. This zoning strategy improves efficiency, lowers carbon impact, and reduces upfront costs by preserving existing air-cooling infrastructure. It also supports a gradual transition, giving operators flexibility to adopt DLC technologies as needed.

Because DLC technologies are evolving rapidly and lack the mature standards that govern traditional air cooling, hybrid cooling provides a practical path to future-proofing data centers, ensuring long-term operational viability and cost effectiveness as cooling requirements continue to change.

When to Use?

Air Cooling
Low/Medium Density

Liquid Cooling
High Density / AI / HPC

Hybrid Approach
Future-Proof Strategy

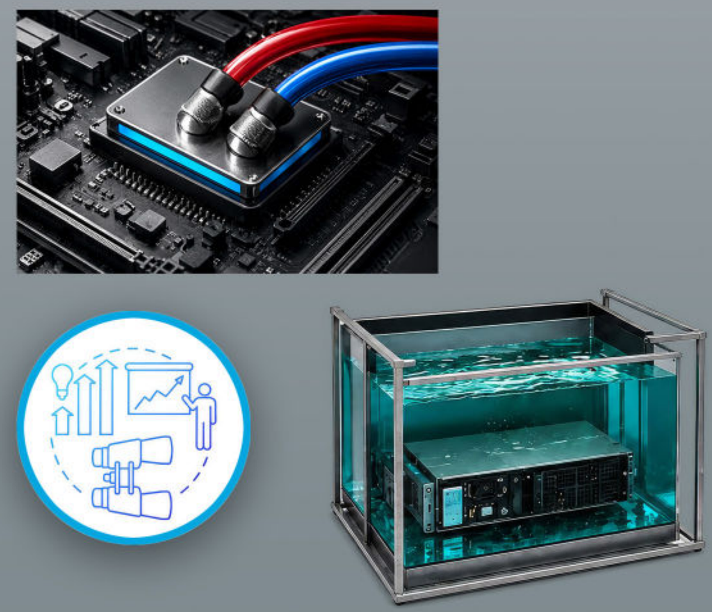
DLC Technologies: Current Leaders and Future Front-Runners

There are two forms of DLC that come to most people's mind even though there are additional types. The first is DTC cooling which is a thermal management approach that removes heat at the source by circulating a liquid coolant in direct contact with high-power IT components. Instead of relying on air to absorb and transport heat, DTC delivers cooling through cold plates mounted directly onto CPUs, GPUs, and AI accelerators. By capturing heat at the chip surface, DTC cooling enables significantly higher power densities and more efficient heat rejection than traditional air based cooling.

Immersion cooling, another form of DLC, submerges the entire server, including all electronic components, within a bath or sealed enclosure filled with a specially engineered dielectric fluid. Because the liquid is electrically non-conductive, it can safely contact energized hardware without risk of short-circuiting. Its high thermal conductivity allows the fluid to absorb heat directly from all of the components, making it more efficient than DTC cooling.

Currently, DTC cooling remains the dominant form of DLC, with the majority of hyperscalers and AI operators treating it as the default path for high-density compute. Market estimates currently put DTC cooling at ~75–80% of all DLC deployments, far outpacing immersion systems.

DTC cooling continues to dominate the DLC landscape primarily because it is significantly easier to deploy, integrate, and operate at scale. Its lower capital expenditure (CAPEX), straightforward maintenance profile, and deployment timeline make it the preferred choice for HPC and AI buildouts.



DTC Versus Immersion Future Market Share

The approach also benefits from a well-developed vendor community and hyperscale familiarity, reducing integration effort and simplifying ongoing operations. By contrast, immersion cooling is still regarded as a niche solution, constrained by higher upfront costs, greater operational complexity, and the facility-level changes required for adoption.

Looking ahead, the long-term trajectory of the DLC market remains uncertain, but industry consensus suggests that immersion cooling will eventually expand beyond its current niche status. Even with this growth, most analysts do not expect immersion cooling to overtake DTC cooling as the dominant DLC approach. Current projections indicate that DTC cooling may retain ~55–65% of the market by 2032, with immersion cooling rising to ~35–45% as adoption accelerates. This shift is expected to be driven largely by hyperscalers, whose scale and operational influence will shape how quickly immersion cooling matures and how the balance between the two technologies evolves.

Data Center Containment

Containment:
The Non-Negotiable Infrastructure

With DTC cooling becoming the preferred implementation of DLC, and with air still required to remove residual heat from high-density racks as well as all heat from low-density racks, containment remains the critical, non-negotiable element of any modern data center thermal strategy. By physically separating hot and cold air streams, containment maximizes the effectiveness of both air and liquid-cooling infrastructure, increases the functional efficiency of cooling equipment, stabilizes inlet temperatures across the ITE, and delivers measurable improvements in energy performance and equipment reliability. This separation enables a smoother and more scalable transition towards the rising thermal demands of AI workloads.

Equally important, containment provides a scalable bridge to the future. When containment is established as the foundational design element, data centers can fully optimize the performance of existing air-cooled systems while preparing for future DLC deployments. It creates a critical transitional layer that allows operators to safely increase rack densities and thermal output over time, delaying the need for capital-intensive DLC adoption until it is operationally justified.

Containment: The Fastest Path to Thermal Reliability & Efficiency

DTC cooling systems remove heat directly from high-power components, but they do not eliminate all rack-level thermal output. Supporting hardware continues to release residual heat into the surrounding air. Without containment to control and direct that airflow, this leftover heat circulates through the data hall, creating localized hot spots and undermining the overall effectiveness of the DTC cooling strategy.

Containment ensures that any remaining heat is captured and directed appropriately. This prevents rack inlet temperature instability and hot spots that would otherwise spread across the data center, preserving predictable thermal conditions and supporting the full value of the DTC cooling investment.

Implementing containment increases the effective cooling capacity of the environment, enabling the infrastructure to support substantially higher rack power densities. Without containment, DTC cooling systems may not be able to handle the higher thermal loads present in high-density HPC racks. For example, without containment the hot exhaust and cold supply air continue to mix, creating unstable thermal conditions, reducing cooling efficiency, and driving up energy consumption. The DTC cooling infrastructure is then forced to compensate for inefficiencies it was never designed to address.

Treating containment as a core design element allows operators to maintain uptime, improve cooling efficiency, and ensure their facilities are prepared for rising thermal demands that come with AI and HPC.

Next-Generation Products for Efficient and Sustainable HPC

Modern data centers need infrastructure built for modern demands, and Subzero's AisleFrame delivers exactly that for AI and HPC environments. Its modular design brings containment, DTC cooling piping, racks, data and power cabling together into a single engineered platform that doesn't rely on a structural ceiling for support. The system deploys quickly, scales cleanly, and supports today's ITE loads while being ready for the higher densities driven by AI.

This frame-based, ground-supported platform, built from steel or an optional composite material, demonstrates that modern data centers no longer need to follow traditional construction methods. Conventional builds depend on multiple vendors delivering separate scopes, each with its own schedule and coordination challenges. AisleFrame replaces that fragmented model by consolidating these elements into one unified structural system. This removes the typical scope boundaries and eliminates the coordination issues that occur when multiple trades work independently.

AisleFrame also simplifies expansion. Its modular construction allows new sections to be added anywhere in the data hall without modifying existing installations, enabling straightforward and repeatable growth as density requirements increase.

The platform is equally effective in retrofit environments, including facilities with concrete slab floors where overhead-dependent infrastructure is difficult to implement. For high-density, DTC cooling driven data centers, AisleFrame provides a scalable structural foundation that supports efficient and sustainable AI and HPC operations today and into the future.

Conclusion

Containment should be the essential first step in any modern data center cooling strategy. Skipping it introduces unnecessary inefficiencies and operational risk, while even in HPC environments containment delivers immediate gains in energy performance, equipment reliability, and overall resilience. It also serves as the critical bridge between existing air-cooling systems and emerging DLC solutions.

Subzero Engineering delivers solutions globally that future-proof facilities, whether implementing containment in existing environments or deploying complete frame-based, ground-supported containment infrastructure in new or retrofitted HPC facilities. The team also provides CFD modeling for design validation, integrates greener materials into the white space, and applies over two decades of data center design expertise. Together, these capabilities reduce Total Cost of Ownership (TCO), strengthen sustainability initiatives, and support long-term energy and carbon-reduction goals.

About the Author

As Senior CFD Engineer at Subzero Engineering, Gordon Johnson leads all CFD initiatives across domestic and international markets. His 30-plus years in the data center industry include efficiency assessments, advanced cooling design, CFD modeling, and disaster-recovery planning. Gordon is a certified DCEP and CDCDP and holds a B.S. in Electrical Engineering from New Jersey Institute of Technology. A frequent speaker and published author, he shares his expertise globally through white papers, research articles, and educational events focused on data center energy efficiency.

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