

White paper

The role of polymer piping in direct liquid cooling

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Abstract

The exponential rise in data processing demands has pushed traditional air-cooling systems to their limits, driving the adoption of direct liquid cooling (DLC) as a superior thermal management solution for modern data centers. Leveraging the high thermal capacity of liquids—approximately 3,500 times greater than air—DLC enables efficient heat removal from high-density IT loads while reducing water consumption and supporting waste heat recovery initiatives. This technical brief explores the critical role of polymer piping systems in ensuring the reliability, efficiency, and sustainability of DLC infrastructures. It examines key performance factors such as corrosion resistance, mechanical robustness, and hydraulic stability, highlighting how advanced polymers like beta-nucleated polypropylene outperform metals in chemical compatibility, coolant purity, and lifecycle sustainability. Additionally, the paper addresses infrared welding technology as a cornerstone for leak-proof, contamination-free connections, and underscores the environmental benefits of polymer systems, including lower embodied carbon and lightweight construction. By combining technical insights with practical implementation strategies, this paper demonstrates how polymer-based solutions future-proof cooling infrastructures, enabling data centers to meet escalating thermal loads and stringent sustainability targets.

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
AWS	American Welding Society
BPE	Bioprocessing equipment
BSRIA	Building Services Research and Intelligence Association
CDU	Coolant distribution unit
CFD	Computational fluid dynamics
CO ₂	Carbon dioxide
CPU	Central processing unit
D2C	Direct-to-chip
DI water	Deionized water
DLC	Direct liquid cooling
DVS	Deutscher Verband für Schweißen und verwandte Verfahren
EN	European Norm
EPD	Environmental product declaration
FWS	Facility water system
GPU	Graphics processing unit
HDPE	High-density polyethylene
IR	Infrared
NDT	Non-destructive testing
PG	Propylene glycol
PP-H	Polypropylene homopolymer
PP-R	Polypropylene random copolymer
PP-RCT	Polypropylene random copolymer with modified crystallinity and temperature resistance
PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride
SCG	Slow crack growth
SCH	Schedule
SDR	Standard dimension ratio
SFN	Secondary fluid network
SS	Stainless steel
QC7	Quick Connect Valve 700
TCS	Technology cooling system
WBI	Weld bead inspection
WHR	Waste heat recovery

1. Liquid cooling – An efficient answer to rising thermal loads

The exponential growth of data processing demands has placed significant thermal management challenges on modern data centers. Traditional air cooling methods are increasingly strained by the high heat densities generated by today’s computing hardware. This has led to a growing interest in alternative cooling solutions, particularly in direct liquid cooling.

Liquid cooling is not a new concept—supercomputers have relied on liquid cooling for decades to manage their extreme thermal loads. Liquid cooling methods provide excellent performance and high energy efficiency because of the superiority of liquid as a heat transfer media. With a thermal capacity on a volume basis approximately 3,500 times greater than that of air, liquid excels in effectively transferring heat. A comparison is provided in Table 1. In practice, this means that present-day air cooling systems can dissipate heat from IT deployments reaching up to 90 kW/rack—though with diminishing efficiency—whereas liquid cooling solutions can reliably and efficiently support rack densities well beyond 100 kW¹.

In air-cooled systems, the coolant temperature is fairly low (around 20°C/70°F), and evaporative cooling is a common method to reject the heat to the environment². Evaporative cooling, however, is a major contributor to the water consumption of data centers, and is therefore deprecated today.

Liquid-cooled systems generally use relatively warm coolants (around 45°C/110°F), compared to air-cooled systems, so that the need for evaporative cooling is drastically reduced or even eliminated². Liquid cooling can then significantly reduce the facility’s water usage and alleviate pressure on regional groundwater supplies.

Furthermore, liquid-cooled systems have the potential to reuse the thermal energy captured from IT equipment. When combined with heat pumps or simply heat exchangers, this energy can be utilized in district heating networks or repurposed for industrial use, an increasingly relevant topic as data centers strive to meet ambitious sustainability and efficiency targets. In Europe, for example, a set of directives and national regulations already encourage or require waste heat recovery (WHR) to reduce energy waste and greenhouse gas emissions.

Table 1: Thermal properties of common coolants

Characteristics (20°C/68°F, 101.3MPa/ 14692.3PSI)	Air ³	Water ⁴	25% Propylene Glycol (PG25) ⁵
Thermal Conductivity [W/(m*K)]	0.025	0.598	0.478
Density [kg/m³]	1.2	998	1024
Specific heat capacity [kJ/(kg*K)]	1.01	4.18	3.98
Thermal capacity per unit volume [kJ/m³*K]	1.2	4176	4075
Dynamic viscosity [cP]	0.0182	1.00	2.86

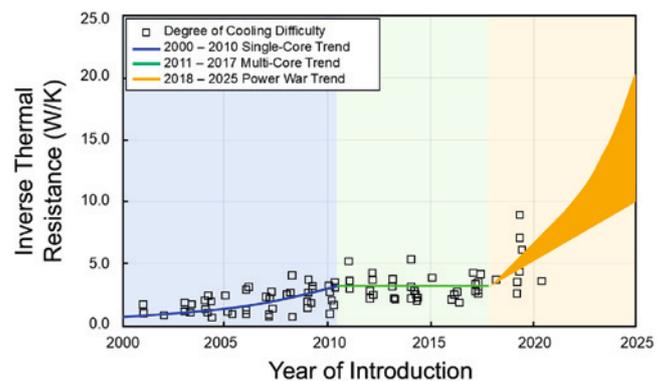


Figure 1: Increase of cooling difficulty of data center IT loads⁶

1. Green Revolution Cooling [GRC], 2024
2. Schneider Electric [SE], 2025
3. Zieliński et al., 2020
4. National Institute of Standards and Technology, no date
5. Castrol ON, 2025
6. ASHRAE Technical Committee 9.9, 2021

2. Types of liquid cooling

The term liquid cooling includes two main varieties: direct liquid cooling and immersion cooling. While direct liquid cooling delivers the coolant precisely to the hottest components via cold plates, immersion cooling takes a more comprehensive approach, fully submerging server hardware in non-conductive coolants.

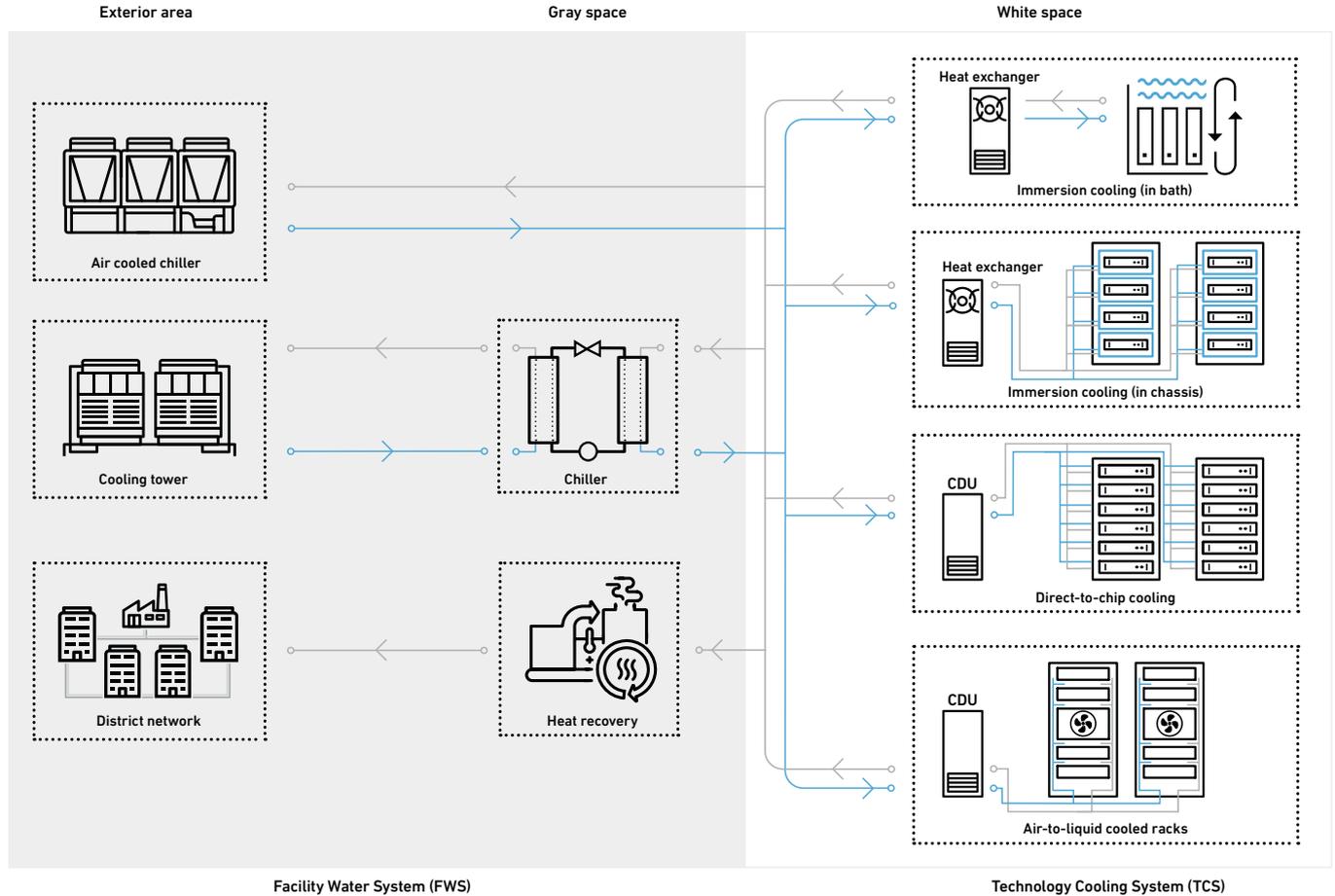


Figure 2: Simplified view of liquid cooling systems in data centers adopted from ASHRAE's definition.⁷

Direct liquid cooling

Of the two types, direct liquid cooling (DLC), sometimes also called liquid-to-chip, direct-to-chip (D2C), or cold plate cooling, is the most common deployment in use by enterprise and hyperscale users.

The heat generated by critical components, such as CPUs and GPUs, is transferred via a specially designed cold plate to the coolant and carried through the piping system to a Coolant Distribution Unit (CDU), the demarcation point between the Technology Cooling System (TCS), sometimes also called Secondary Fluid Network (SFN), and the Facility Water Systems (FWS).

CDUs are packaged or skidded mechanical equipment containing pumps, a heat exchanger, controls, and hydronic components that manage the temperature of the chips by regulating the flow and by exchanging heat with the FWS, and, with that, regulating the coolant temperature.

Additionally, CDUs maintain the liquid purity and quality with integrated filters, sensors, and by isolating the TCS as a closed-loop.

The FWS rejects the heat to the environment or to a waste heat recovery system. Subsequently, cooled liquid is supplied to the CDU.

As the sole interface in direct contact with the heat source, i.e., the chip, the optimal performance of the cold plate is of paramount importance for the entire system's efficiency and longevity⁸. Cold plates contain tiny micro-channels designed to enhance heat transfer. Tiny particles or other impurities can easily clog these channels. To prevent cold plate fouling, it is crucial to maintain a high liquid purity and quality and to avoid biological growth. Therefore, propylene glycol (PG) and

7. American Society of Heating, Refrigerating and Air-Conditioning [ASHRAE], 2019

water solutions enriched with selected additives, like corrosion and organic growth inhibitors, are commonly used⁸. Additionally, the systems are equipped with fine filters.

Commonly, liquid cooling systems are single-phase systems, i.e., the coolant stays liquid throughout the complete cooling loop. However, in some cases, two-phase systems are used. These coolants have a low boiling point so that they evaporate while cooling the chip and then condense back to liquid and reject heat energy at an external condenser².

Compared to traditional air cooling systems, DLC systems offer superior thermal and energy performance¹. However, DLC only cools critical components, such as server CPUs and GPUs, responsible for approximately 70% - 80% of the total heat load of the white space¹. The remaining components still require traditional air cooling, making the ecosystem a hybrid cooling system. However, as most of the heat is expelled with DLC, the need for air cooling is significantly reduced, resulting in a reduction of energy consumption and fan noise².

One practical advantage of DLC over other types of liquid cooling is its general resemblance to other common cooling systems. Data center operators are realizing that their legacy air cooling systems can no longer support the IT equipment specifications that their tenants or internal customers require. DLC provides an effective, reliable, and scalable solution to address such retrofit or build-out challenges.

Direct-to-chip liquid cooling is the most widely used form of liquid cooling in data centers today, efficiently removing heat directly from CPUs and GPUs through closed-loop cold plates and piping, while allowing for scalable and straightforward integration with existing air-cooled infrastructure.

Immersion Cooling

For high-density new data center builds, immersion cooling offers the highest performance potential. Like DLC, it can be designed as a single- or two-phase system. However, here, the servers are immersed in a dielectric fluid, which directly contacts all heat-emitting components, providing two key benefits: optimal thermal connection without intermediate layers, and elimination of additional air-cooling. The system also runs almost silently, as there are no fans.

These features give immersion cooling a performance edge over DLC, removing over 95% of the heat via liquid². Despite its potential, adoption remains limited due to scaling problems as well as the need for new procedures and equipment, which data center owners adopt cautiously^{1,2}.

Immersion cooling fully submerges servers in a non-conductive liquid, achieving the highest cooling performance by eliminating thermal interfaces and air cooling needs. The wider adoption is however today limited by scaling challenges as well as the need for new procedures and equipment.

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1. Green Revolution Cooling [GRC], 2024
 2. Schneider Electric [SE], 2025
 8. Chinthaparthi L.S.R., 2024

3. Empowering sustainable cooling with reliable liquid conveyance in DLC

Escalating heat densities and the imperative for enhanced energy efficiency are driving the wider adoption of direct liquid cooling. As the industry evolves, the liquid conveyance infrastructure plays a pivotal role in determining the long-term success of these mission-critical cooling systems, delivering performance and reliability for the entire cooling function.

3.1 Piping materials in data centers

Although direct liquid cooling is just beginning to be applied on a wider scale, the conveyance of liquids is not a novelty in data centers. For decades, facility water systems (FWS) have been an integral part of data centers, including various liquid processes such as chilled water, condenser water, evaporative water, domestic water, chemical treatment, process water, and reheat and heat recovery. As such, data centers have witnessed various generations of piping materials become prevalent. The industry has moved from carbon steel and copper lines to today's stainless steel pipes⁹ and will likely see the rising adoption of polymers in the future.

Each transition was primarily driven by the quest for improved performance, enhanced reliability, or greater economic efficiency. E.g., today's commonly installed high-quality stainless steel grades SS304 and SS316 have replaced copper mainly due to corrosion and liquid purity considerations in TCS loops.

The general prevalence of steel is historically based on trade familiarity, wide availability, and advantages compared to polymers in extreme pressure and temperature applications. In DLC systems, however, the operating conditions are within the boundary parameters for polymers⁹, and the excess strength of steel comes with the cost of heavy weight, coupled with long build and flushing times.

Moreover, the industry's shift toward performance optimization through new coolants and increasingly miniaturized cold plate features—ultimately approaching microfluidic structures directly on the chip¹⁰—demands higher coolant purity and extensive chemical compatibility. Both areas in which high-performance polymers outperform steel.

High-performance polymers are engineered materials to meet the mechanical, chemical, and thermal needs of demanding, mission-critical industries such as semiconductor manufacturing or data centers. Common polymers used in industrial piping systems include PVC (Polyvinyl Chloride), also referred to as vinyls, HDPE (High-density Polyethylene), PP (Polypropylene), and PVDF (Polyvinylidene Fluoride). As an engineered solution, the detailed product properties vary depending on the producer.

A fundamental benefit of polymer piping is its inherent corrosion resistance in contrast to metallic materials, which are susceptible to many types of corrosion. In data center cooling systems, the use of coolants enriched with corrosion-inhibiting additives, has solved this issue. However, this adds complexity to the liquid monitoring and dosing system, so that the interest in corrosion-free solutions is on the rise.

3.2 Elevation of pure water as a coolant

The race towards optimized performance and increased efficiency is fueling the need for new coolant options. Today, a 25% mixture of propylene glycol (commonly called PG25) and water is commonly used⁵. In addition to corrosion inhibitors, this mixture is further enriched with additives to prevent freezing during shipment and installation, to avoid foam, pH changes, and biological growth.

When glycols are added to water, the overall cooling performance declines as the thermal conductivity and specific heat capacity decrease while the density and viscosity increase¹¹. A simple comparison is given in Table 1. This means that a DLC system using water, in particular deionized (DI) water, can remove heat more effectively, potentially allowing for higher server densities and reduced pumping rates. For example, in a 70m (230ft) long DLC loop with a d160 (6") pipe and $\Delta T=10^{\circ}\text{C}$ (18°F), the relative pressure loss with DI water is approximately 13% lower compared to PG25 due to its lower viscosity contributing to a reduction in pumping power of about 16%.

Since deionized water lacks dissolved minerals, it is highly corrosive. When metals corrode, they react with elements in their environment (like oxygen and water) to form new chemical compounds. While the metal itself is lost to the circulating liquid, it is converted into larger, solid, and adhesive corrosion products that accumulate on the inner walls of the pipe¹². This causes material degradation and liquid contamination over time. In contrast, polymer piping systems,

5. Castrol ON, 2025

9. Mitchell, D. et al., 2024

10. Microsoft, 2024

11. Azarifar M. et al, 2024

12. The Electrochemical Society, no date

even capable of handling much more aggressive ultrapure water, remain inert with deionized water and, therefore, allow for higher efficiency without compromising system integrity.

An exemplary calculation on corrosion depth and particle release is given in Figure 3. One meter SS304, SS316, and polymer pipes are compared over a 10-year span in J-13 well water (low chlorine, near-neutral pH). The corrosion rate in such condition varies between 0.02-0.57 $\mu\text{m}/\text{year}$ ¹³. Higher corrosion rates of 0.87 $\mu\text{m}/\text{year}$ for SS304 and 0.77 $\mu\text{m}/\text{year}$ for SS316 are given in a humid atmosphere¹⁴. The range is considerable. While a particle release of only 35 mm^3 (0.002 in^3) over ten years can be expected in the best case scenario, it can rise up to 1500 mm^3 (0.09 in^3) over ten years, assuming a corrosion rate of 0.87 $\mu\text{m}/\text{year}$.

Corrosion depth in 10 years [μm]
Pipe dimension: SS SCH10 / 2" OD: 60.3 mm, WT: 2.77 mm

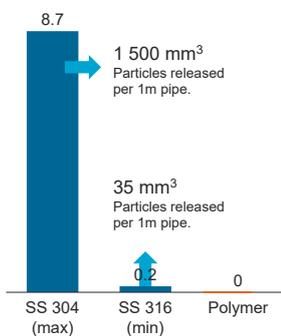


Figure 3: An exemplary calculation in 10 years of pipe use in water conditions using the maximum and minimum corrosion rates from literature.

3.3 Enhanced coolant purity and quality to prevent cold plate fouling

To improve the coolant purity and maintain the cold plate performance, the filtering requirements of DLC systems are rapidly developing. A similar trend of rising purity requirement was previously witnessed in semiconductor manufacturing. Today's norm of filtering 25-50 μm particles⁹ is foreseen to tighten to 10 μm soon.

Still, the requirement is far from the standards used in semiconductor fabrication. Currently, the prevalent standard for ultrapure water applications in semiconductor processing, the SEMI F63, demands the critical particle size to be below 5 nanometers (0.005 μm), 20 times smaller than the strictest requirements in DLC systems today. This requirement can only be met using high-performance polymers.

Filtration causes significant pressure loss in DLC systems but is necessary to remove any released particles before they accumulate and cause damage to sensitive equipment and components like pumps, valves, and especially the cold plates. Still, as the cold plate sits halfway through the DLC loop, there is a 50% chance that contaminants released from the piping first reach the cold plate and its micro-channels before being filtered from the liquid.

Polymer piping, able to fulfil even the strict standards of ultrapure water systems, can significantly reduce the risk of clogging and fouling while also mitigating the need for complex and frequent micron-level filtration. Ultimately, this minimizes pressure loss, lowers maintenance requirements, and reduces costs while guaranteeing consistent operation.

3.4 Surface smoothness

Another fundamental benefit of polymer piping over metals is its exceptionally smooth surface originating from the manufacturing, as well as from the lack of corrosion, as discussed previously.

Sustained hydraulic performance

Corrosion and scaling develop internal roughness in metal piping over time, leading to higher frictional losses and reduced internal diameter. As the relationship between volumetric laminar flow rate, Q , and pipe diameter, D , is proportional to the fourth power of the diameter, $Q \propto D^4$, even small changes in diameter significantly affect the flow. Therefore, corrosion control in metal piping is essential. Polymer piping does not corrode, giving predictable flow characteristics and eliminating the need for over-dimensioning the piping system to compensate for future internal degradation.

An exemplary calculation of turbulent flow in a 1m (3.3ft) long, DN50 (2") stainless steel pipe is given in Figure 4. It is assumed that the surface roughness increases from $k=0.015\text{mm}$ to 0.03 mm , and the corrosion product layer (including occluded areas, biofilm, and deposits) builds up on the pipe surface to a total of 0.5 mm over 10 years in 20°C (68°F) water use. This results in a 4% decrease in flow area and a reduction of 8% in the volume flow rate over a ten-year span.

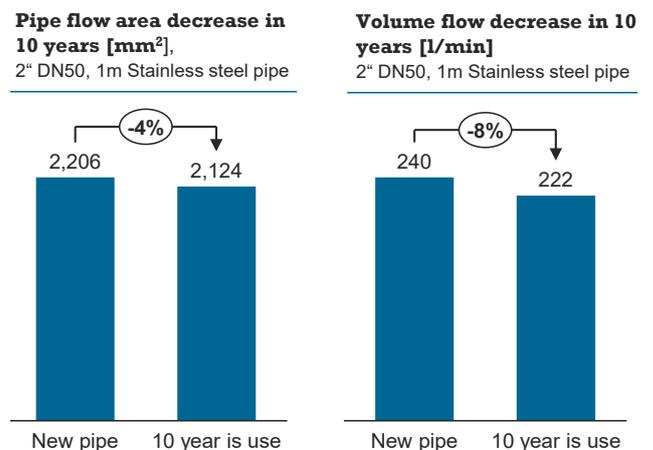


Figure 4: An exemplary calculation of turbulent flow in a 1m, DN50 stainless steel pipe, assuming that the surface roughness increases from $k=0.015$ to 0.03 mm , and the corrosion product layer builds up on the pipe surface in a total of 0.5 mm over 10 years.

9. Mitchell, D. et al., 2024
13. He, Ahn and Sippel, 2012
14. Ul-Hamid et al., 2017

Inhibiting biofilm formation

The typical surface roughness for polymer piping is $0.007\mu\text{m}$ in comparison to $15 - 0.1\mu\text{m}$ for steels, depending on the grade and the surface treatment¹⁵. Achieving fine surface smoothness in metal piping is possible with the additional step of electropolishing. However, this increases the initial capital expenditure and prolongs the commissioning phase of the DLC system.

Surface smoothness not only affects flow friction but also adhesion and growth of biofilm^{16,17}. Biofilm buildup can restrict flow, reduce heat transfer efficiency, and necessitate the use of aggressive chemical additives for control. Furthermore, the chemicals used to treat biofilm can be corrosive and may damage sensitive piping system components such as cold plates. By minimizing biofilm formation, plastic piping reduces the reliance on such additives, leading to potential cost savings and a more environmentally benign operation. Biofilm growth on different piping materials is shown in Figure 5.

Biofilm growth on different piping material for data centers

Biofilm test in standing pure water system

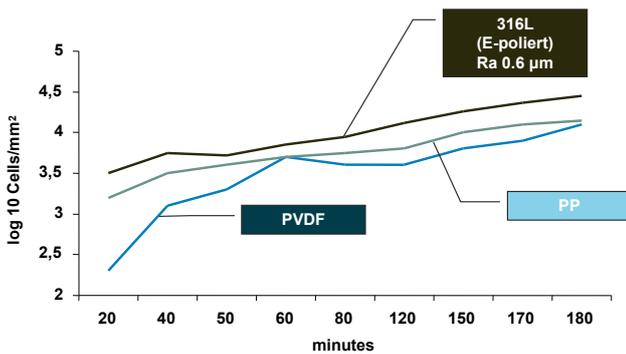


Figure 5: Biofilm test in standing pure water system.

In direct liquid cooling systems, piping plays a crucial role in enabling efficient system performance. With increasing heat densities and rising concerns about energy consumption, the optimization of flow and heat transfer is essential.

The initial selection of the coolant, the preservation of its performance, and the maintenance of a smooth pipe surface are key to achieving a reliable and efficient thermal management.

15. The engineering toolbox, no date

16. Hyde, F.W., Alberg, M. and Smith, K., 1997

17. Gillis and Gillis, 1996

4. Polypropylene – piping material tailored for critical industrial applications

Polypropylene is a widely versatile and commonly used polymer in various industrial and consumer applications. Its excellent balance of properties in cost-efficiency, chemical resistance, and mechanical strength even under high temperatures make it a core technology also for DLC.

4.1 Superior chemical resistance

Polypropylene is a semi-crystalline polymer whose crystalline phase can occur in various modifications, depending on whether and how the material is nucleated. The type and amount of the crystalline phase significantly influence both its chemical and mechanical properties.

A special form, beta-nucleated polypropylene homopolymer (beta PP-H), material offers superior chemical resistance and long-term durability compared to standard polypropylene and metal alternatives. The beta modification significantly increases the toughness compared to the standard (alpha) material due to the superior morphology shown in Figure 6. The beta modification is realized by adding special nucleating agents. Dedicated processing helps to form a homogenous and fine structure with minimal internal stress, further improving the overall performance.

Moreover, beta PP-H offers enhanced chemical resistance, particularly relevant for DLC systems, which utilize various coolants with a broad spectrum of additives to optimize the system performance. Beta PP-H is tested to withstand long-term exposure to aggressive chemicals at elevated temperatures, and proven by 30 years of experience in field use¹⁸.

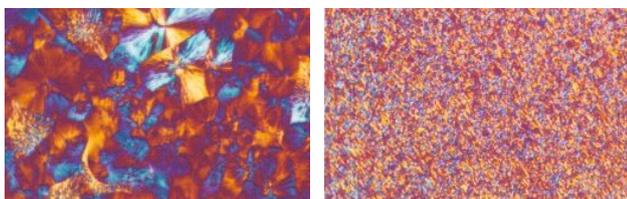


Figure 6. Structure of non-nucleated PP-H (left) and nucleated Beta-PP-H (right) (magnification = 80x; transmitted light, polar; 15 µm microtomic section)

4.2 Mechanical robustness and dimensional stability

Erosion is a common challenge in liquid-cooled data centers, particularly at points of high flow velocity, such as the outlet of CDUs. High-performance polymer piping, like beta-nucleated PP-H, offers a significant advantage over metals: it is more resilient to erosion due to its higher maximum velocity tolerance.

Excellent mechanical strength is needed in data center construction and operation, where piping systems may be subject to vibrations, thermal cycling, accidental impacts, and the risk of seismic stress. Unlike metals, whose extreme strength comes at the cost of weight, high-performance polymers provide an optimal balance of strength and lightweight design. The mechanical strength of beta PP-H is compared to that of polypropylene with lower crystallinity (PP-R) in Figure 7. Higher crystallinity leads to higher strength and stiffness, resulting in better impact resistance, e.g., against accidental damage. Furthermore, the rigidity of beta PP-H allows for full piping systems, while PP-R is too flexible a material for pressure components like valves, for example. Moreover, the higher rigidity of beta PP-H allows for longer bracketing distances as rigid material does not bend and sag.

PP-RCT, neglected in this comparison, is a beta-nucleated derivation of PP-R, with an improved long-term, pressure resistance in elevated temperatures. In the short term the mechanical properties of PP-RCT are similar to PP-R. In terms of chemical resistance PP-RCT is better than PP-R, but does not reach the level of PP-H.

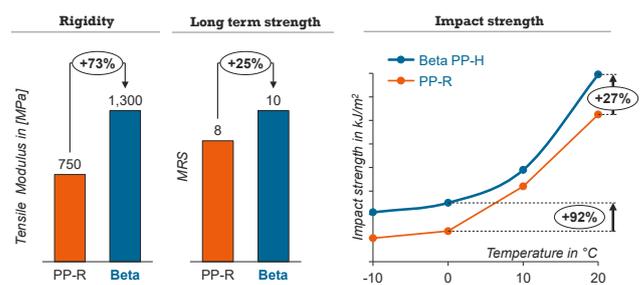


Figure 7: Comparison of mechanical properties of polypropylenes according to ISO15494 requirements. Impact strength was measured as notch impact test with laboratory samples for comparison. The technical data sheet of the Beta PP-H gives 50kJ/m² and for PP-R 20kJ/m² at 20°C.

18. Georg Fischer, 2003

4.3 Chlorine, copper, and salt resilience in DLC environments

The presence of chlorine and salts such as chloride and sulfate has caused serious issues with polymer piping in municipal applications¹⁹. These concerns have been raised in data center applications as well as they may be present in DLC coolants^{7,20} but are unfounded.

Chlorine, a strong oxidizer, chemically attacks the piping (oxidation), causing the pipe surface to become rough. This roughness can lead to slow crack growth (SCG). The presence of copper particles and ions accelerates this process, as copper acts as a catalyst.

Chlorine does not pose a risk to beta PP-H materials in DLC where high, long-term chlorine levels are unexpected. Unlike municipal water systems, where the water is intended for human consumption, DLC systems do not require bacteria and virus-killing functions. Therefore, chlorine levels are not maintained, and any free chlorine is quickly dissipated. Furthermore, as indicated in GF's chemical resistance tool²¹, GF's DLC system is unconditionally applicable to continuous exposure to chlorine concentrations up to 2ppm at temperatures up to 60°C (140°F) with a lifetime expectancy of 25 years.

With the exception of the cold plate, DLC systems use few copper-containing components compared to plumbing installations, where brass lines and fittings are frequently used. Therefore, copper leaching is expected to be low and, based on extensive industrial experience, is not considered critical for GF's DLC system material, provided the following risk scenarios are avoided:

- There are elemental copper/copper alloys in direct physical contact with GF piping (e.g., in brass transition fittings) while the medium also contains copper or other transition metal ions, creating a redox environment. This risk scenario can be mitigated by avoiding direct connections to elemental copper parts.
- There is frequently replenished oxygen in the water (like in a hot water recirculating line in building applications). In the presence of mixed metal ions, this creates a redox environment. This is, however, considered an unlikely scenario in DLC use.
- Free chlorine and copper (ions) are present at the same time over prolonged periods of time, especially at elevated temperatures and pH values below 7. As discussed above this scenario is also unlikely in DLC use due to rapid dissolution of chlorine.

As the AI computing industry advances, the materials selected for the pipework become increasingly important. High-performance polymers, such as polypropylene, have emerged as a premier solution due to their positive effects on coolant purity and inherent advantages in chemical and mechanical properties, as well as cost efficiency.

7. American Society of Heating, Refrigerating and Air-Conditioning [ASHRAE], 2019

19. Replumb Specialties Inc., 2024

20. IBM, 2025

21. GF Piping Systems, no date

5. Precision welding – the key to reliable, leak-proof systems

The biggest risk for leaks in the piping system lies in the connections. Infrared fusion is the most reliable welding technology, specifically developed for mission-critical environments.

5.1 The fast and clean infrared welding

Piping system integrity is highly dependent on the reliability of its joints. To fulfil the high demands of DLC systems, clean, homogeneous, and highly reliable connections are required which can only be achieved with infrared (IR) welding. IR welding is a non-contact jointing method that utilizes infrared radiation to precisely control the temperature and to create a molecular bonding, as shown in Figure 8. The absence of direct contact, welding gas, or any fillers eliminates the risk of contamination, ensuring the highest weld reliability and a 100% purity of the liquid pathway, as no contamination is released inside the piping loop during the IR welding process of polymers.

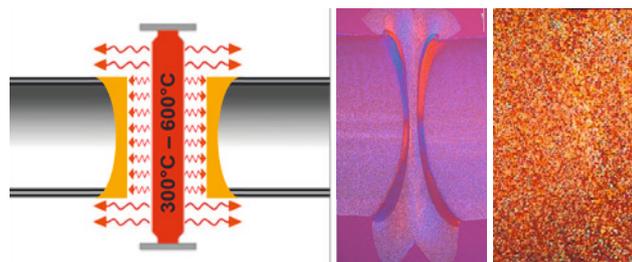


Figure 8: Infrared fusion method (illustrated on the left) results in low stresses at the weld (in the middle) and uniform crystallinity across the welded area (on the right) showing the pipe inner surface in transmitted light, polarized 48x magnification. Picture width corresponds to the welding zone.

Metal-welded piping should be cleaned and passivated prior to commissioning, as suggested by various standards such as ASME B31.3, AWS D10.18, and ASTM A380/A967^{22,23}. Cleaning is needed to remove the welding residues, and passivation allows the natural chromium oxide protection layer of stainless steel to form and regenerate. As this process involves acid solutions and other chemicals a thorough post-passivation flush is essential⁹.

Since polymers do not corrode, passivation as well as the subsequent flushing can be avoided. Also, the IR welding releases zero contamination to the piping loop. As BSRIA notes, polymer pipework “presents fewer dirt-related problems than steel and copper pipework, as jointing methods are usually cleaner and there is no risk of corrosion”²⁴. Consequently, the flushing needs of up to 8 weeks in the commissioning phase can be reduced significantly.

5.2 Exceptional joint strength and reliability

Generally, low stress at the weld is key for reliable joints, regardless of the piping material. Stress accelerates both mechanical cracking and chemical vulnerability.

Since IR welding enables minimal internal stress and uniform crystallinity in the weld, it significantly reduces the long-term risk of joint failures. Crystallographic studies have shown (Figure 8, Figure 9) that the polymer nucleation phase forms again in the welding area after the IR welding process. The material properties at the weld retain up to 96% of the base material strength according to tensile tests per DVS guideline 2203-5. This is well above the required minimum of 60% and indicates superior joint quality. As the material thickness in the welded area also increases, this area is generally stronger than the original pipe. In contrast, the welded area of metal pipes is the risk area due to heat treatment and a mix of particles.

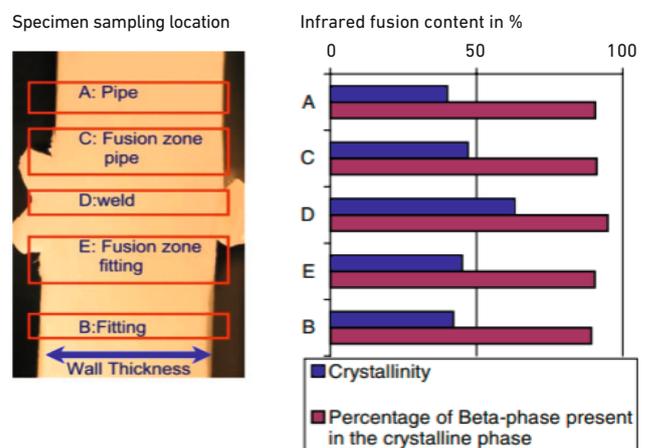


Figure 9: The material properties in the IR-welded area reform, eventually equaling the properties of the unwelded pipe. Illustration of the sampling section on the left and the material structure analysis (WAXS) in each section on the right. Specimen size 10x10x1 mm for an IR weld of 110 x 10 on Beta-PP-H.

9. Mitchell, D. et al., 2024
 22. ASME, no date. AWS, no date
 23. ASTM international, no date
 24. BSRIA, 2020

The precise temperature and pressure control of IR fusion machines decreases stress and results in small weld beads, as illustrated in Figure 10. As weld beads can interfere with the flow and facilitate biofilm growth, smaller weld beads are generally desired. The appearance of a fusion weld bead varies based on the technology, the material, and several other essential factors, such as temperature control, alignment precision, and environmental conditions. These factors are all critical for creating consistent, high-quality welds for mission-critical applications.

IR welding delivers joints with up to 96% of the base material's strength. This technology ensures clean, homogeneous connections with zero contamination risk and minimal flushing requirements during commissioning. Unmatched reliability is achieved through full automation and comprehensive digital traceability of every weld.

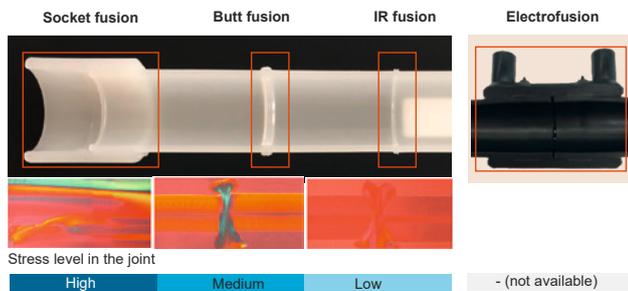


Figure 10: Weld bead in different polymer fusion technologies.

Automation and control ensure reliability

With more than 500 high-performance fusion machines in use at 15 pre-fabrication facilities around the globe, GF records more than 25 million IR welds annually. According to this data, on average, only one failure occurs per 2.4 million welds. Such remarkable reliability is a result of the high degree of automation that GF employs in its IR welding machines.

Automated IR welding machines monitor and adjust environmental parameters such as altitude and ambient temperatures as well as welding parameters such as heating time, material temperature, and pressure in real-time, to ensure the integrity of each weld. For complete traceability, each weld and the corresponding parameters are stored under a unique weld ID and can be retrieved afterwards. Additionally, state-of-the-art digital inspection, e.g., with the weld bead inspection (WBI) tool or by ultrasonic non-destructive testing (NDT), can be applied if the extra step in quality control is needed. This provides extra peace of mind in mission-critical applications.

GF's total quality management approach focuses on automation and digital inspection for one simple reason: Across all industries and segments, joint failures are rarely technology-related—the vast majority is caused by human errors and machine mishandling. Therefore, automation and digital quality control of welding is indispensable for mission-critical applications like DLC.

6. Growing emphasis on sustainability

In an era of increasing environmental awareness, the sustainability of data center infrastructure is paramount. Polymer piping systems offer a compelling value proposition.

6.1 Lower embodied carbon emissions and waste

Overall, the production of polymer piping generates substantially lower carbon dioxide (CO₂) emissions compared to the energy-intensive manufacturing of metal piping. This disparity is a key factor driving the lower embodied carbon associated with polymer systems in comparison to metals.

An example comparing a stainless steel (SCH10/EN 10357/ ASME BPE 4") to a polymer (PP-H d160/SDR17.6) piping system in Schneider Electric's EcoStruxure reference design 109²⁵ is shown in Figure 11. In this case, exchanging a stainless steel with a polymer system reduces the embodied carbon on a system level by 51%.

The CO₂ values in this example are calculated for the raw material phase (A1) of the product life cycle using the ecoinvent database²⁶, as well as product EPDs where available. An operational carbon comparison should be based on data from actual data center operations that for this EcoStruxure reference design 109 is not available.

It should be noted that today's underdeveloped plastic recycling processes potentially decrease the difference between polymers and metals in cradle-to-grave life cycle assessments, as for metals, the recycling is more commonly available. On the other hand, the long lifespan of high-quality polymer systems, often exceeding 25 years, mitigates this issue. Reducing the frequency of replacement significantly impacts the associated resource consumption, emissions, and waste generation. As such, the full sustainability analysis is complex and requires further research.

6.2 Lightweight for efficient logistics and construction

The lower density of polymers compared to stainless steel results in significantly lighter systems (Figure 11), offering substantial benefits throughout the project lifecycle. For instance, the Schneider reference design²⁵ used as the example is 64% lighter when constructed from polymer piping instead of stainless steel.

In general, lighter components offer various advantages. On the one hand, these are simpler to handle for on-site personnel and do not require heavy lifting equipment, lowering the risk of accidents while allowing for more efficient construction processes. On the other hand, reduced weight directly translates to simpler logistics and lower carbon emissions during transport.

Additionally, weight limitations can constrain the size of prefabricated modules. Large, prefabricated modules are desirable as these accelerate on-site assembly and allow for quicker commissioning.

25. Schneider Electric [SE], no date
26. ecoinvent Association, 2024

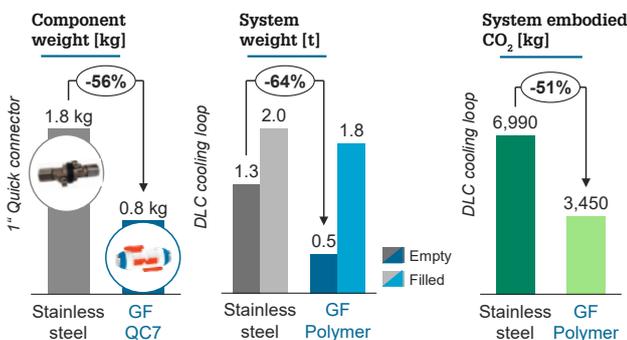


Figure 11: Comparison of valve components and an entire DLC loop based on Schneider Electric's EcoStruxure reference design 109. CO₂ calculation shows values only for phase A1 (raw material). Generic data set "world" from ecoinvent is used.

6.3 Thermal performance driving energy efficiency

Polymers offer inherently lower thermal conductivity (~0.23W/mK for PP-H²⁷) than metals (~16W/mK for SS316²⁸), minimizing heat transfer from liquids to the surroundings. In white spaces, this results in more heat being carried out by the DLC system rather than escaping to the air and eventually straining the white space's air conditioning. In addition, if a WHR system is employed, a greater share of the heat can be reused directly from the DLC loop. The first WHR systems in data centers have been commissioned, for example, in Finland and Sweden²⁹, and, driven by regulations and environmental concerns, the topic of heat reuse is on the rise.

Further energy savings can be achieved with pre-insulated polymer piping, which, in the case of the Baden Cloud Data Center in Appenweier, Germany, resulted in an impressive 30% higher energy efficiency³⁰.

The energy-intensive manufacturing of metal products is the primary reason for the substantial embodied CO₂ savings achieved by using polymer piping systems. In addition, their lightweight nature underpins many of the associated sustainability advantages and handling benefits.

27. GF Piping Systems, PROGEF, no date

28. SteelPRO Group, no date

29. Paulsson, Lundgren and Pohjanpalo, 2025

30. Georg Fischer Piping Systems Ltd and Leitwerk AG, 2023

7. From potential to practice

While there are clear performance, reliability, and sustainability benefits of polymer piping systems, the successful implementation in direct liquid cooling systems depends on the ability to translate theory into reality. This is where engineering know-how, proven product quality, and a system-level understanding become essential. GF brings decades of experience in mission-critical piping applications and a portfolio of solutions purpose-built for the cooling demands of data centers.

7.1 High-performance solutions for optimal flow

GF's direct liquid cooling portfolio, LiquidCore³¹, is specifically engineered for optimal flow performance. Improved flow characteristics minimize the pressure drop of the cooling loop, and directly translate to reduced circulation pump power consumption—a significant operational cost in data centers. For instance, GF's novel Quick Connect Valve 700 (QC7) features an approximately 10% larger opening, resulting in a roughly 25% improved flow compared to the currently prevalent solution^{32,33}. Similarly, GF's round manifold design provides a better flow performance than traditional rectangular manifolds, enabling higher rack densities while maintaining similar outside dimensions.

An exemplary simulation is illustrated in Figure 12 and Figure 13. The figure shows the maximum rack density that can be reached while maintaining a pressure drop lower than 50mbar (0.73psi) per manifold. Simulations are carried out with PG25 as the heat transfer liquid at 30°C (86°F) and in a manifold of 44 branches equipped with quarter-inch couplers.

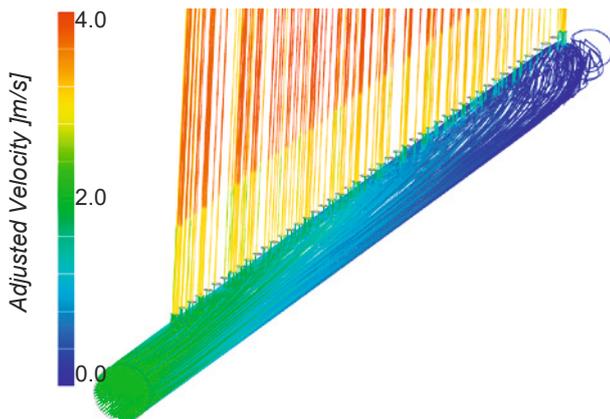


Figure12: Flow simulation of a manifold of 44 branches equipped with quarter-inch couplers.

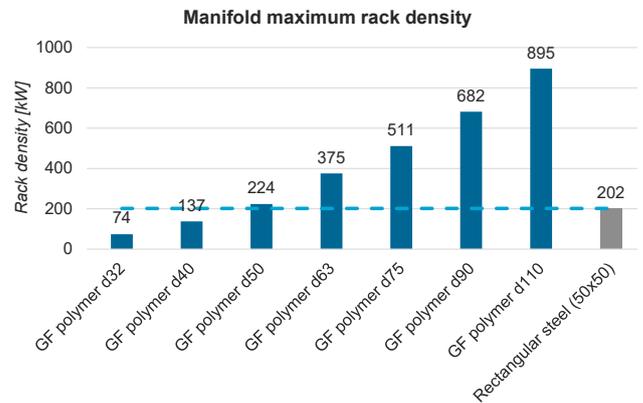


Figure13: Simulation of maximum rack density (kW) with various manifold designs with PG25 coolant at 30°C and limited by a maximum pressure drop of 50 mbar per manifold.

7.2 Uncompromising quality and reliability

To safeguard critical operations, GF's piping systems and components are manufactured and tested to stringent international quality standards. Long-term performance is verified through static and dynamic testing, including burst and drop tests, thermal cycling, pulsation resistance, and endurance simulations.

GF offers:

- 100% leak testing for its DLC system components
- Warranty as a single source of responsibility

This uncompromising quality management ensures leak-free performance and operational reliability even in the most demanding data center environments.

31. GF Piping Systems, LiquidCore, no date

32. Staubli, 2024

33. Danfoss, 2025

7.3 More than 35 years of proven expertise in mission-critical environments

GF has extensive experience in providing piping systems to the most demanding industries, such as the microelectronics industry, where ultra-high purity, material performance and delivery of operational commitments are essential. The company's ability to meet the rigorous standards of these industries is demonstrated through multiple awards recognizing excellence in supplier performance and quality, e.g., the Intel EPIC Supplier Award (most recently for 2025) and TSMC's Excellent Performance Award.

7.4 State-of-the-art welding technology

Mission-critical applications, like DLC, require highly reliable connections. With these applications in mind, GF has been pioneering infrared fusion welding for polymers since 1991. Considering that the majority of weld issues are human-induced, intelligent automation along with full traceability to ensure accountability and to facilitate post-installation inspection, are key to avoid costly mistakes.

For this reason, GF takes a holistic approach offering state-of-the-art automated welding technology, along with sophisticated, non-destructive inspection tools, and a digital platform enabling full traceability. Furthermore, GF provides certified, high-quality training for its machinery customers.

7.5 Prefabrication

GF provides extensive prefabrication services out of 15 prefabrication facilities around the globe. As approximately 40% of piping failures occurring in the first 5 years are reported to be caused by installation errors³⁴, prefabrication is the key to improved reliability. Large, prefabricated spools that are tested and manufactured in controlled factory settings minimize the number of connections on site. This drastically reduces the likelihood of installation errors⁹.

Prefabrication also speeds up the installation process and reduces the need for a skilled, specialized workforce at the site. The significant time benefit achievable with prefabrication and off-site manufacturing has been demonstrated by a hyperscaler in Ireland, which was able to reduce the on-site installation time from 6 months to 6 weeks³⁵.

7.6 Engineered with expertise

As the leading supplier of polymer piping systems for industrial applications, GF is widely experienced to support its customers also in design. Our advanced engineering service includes safe conversion of metal designs to polymer designs with full computational fluid dynamics (CFD) capabilities for flow optimization. GF also provides pipe stress analysis, safe bracketing design, and seismic analysis accompanied by a certified training program for installers.

GF LiquidCore portfolio delivers high-performance liquid cooling with optimized flow, reducing energy use and enabling higher rack densities. Backed by rigorous quality standards, advanced welding technology, and prefabrication services, GF ensures reliability and fast installation. With global reach and engineering expertise, GF provides end-to-end solutions for mission-critical data center environments.

9. Mitchell, D. et al., 2024

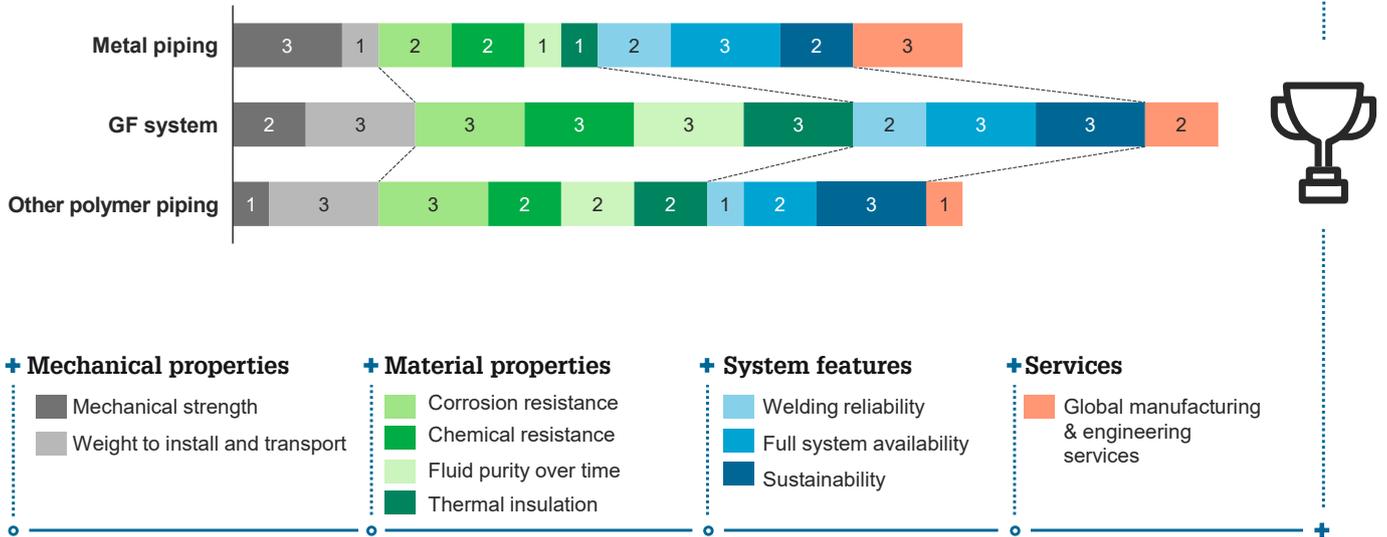
34. Plastic Pipe Database Committee, 2024

35. Georg Fischer Piping Systems Ltd, 2023

8. Conclusion – Future-proof your cooling infrastructure

Comparison of different piping systems for data centers

3= best performance, 1= lowest performance between the compared groups



+ Mechanical properties

- Mechanical strength
- Weight to install and transport

+ Material properties

- Corrosion resistance
- Chemical resistance
- Fluid purity over time
- Thermal insulation

+ System features

- Welding reliability
- Full system availability
- Sustainability

+ Services

- Global manufacturing & engineering services

Global reach, local support

GF is dedicated to supporting its customers throughout every stage of their projects—from planning to commissioning. With sales companies in 33 countries and 40 manufacturing sites worldwide, GF operates on a "local-for-local" basis, ensuring customers benefit from responsive service, short delivery times, and tailored technical support. 15 fabrication hubs around the globe further accelerate project timelines by enabling parallel manufacturing and simplified on-site installation. GF is your trusted partner for constructing data centers worldwide—whether in Seattle, Schaffhausen, or Singapore.

The data center industry's relentless pursuit of enhanced cooling efficiency and sustainability has led to the rise of direct liquid cooling (DLC). Within this evolving landscape, the choice of piping system is paramount to ensure the long-term performance, reliability, and environmental responsibility of these advanced cooling systems.

GF stands at the forefront of this evolution, championing the use of high-performance polymer as the superior alternative to traditional metal piping. High-performance polymer piping systems offer a compelling combination of advantages: long-term corrosion resistance, ultra-smooth internal surfaces, and leak-proof infrared fusion technology. These attributes translate to improved hydraulic performance, expanded coolant compatibility, enhanced coolant purity, quick and reliable installation and deployment, and reduced overall costs.

Moreover, the lightweight nature of polymer piping, coupled with its ease of handling and installation, enables the construction of larger prefabricated modules, adding reliability, accelerating project timelines, and improving worker safety. Its lower thermal conductivity minimizes heat loss, maximizing energy efficiency, particularly in applications involving waste heat recovery.

Importantly, the manufacturing of plastic piping results in significantly lower carbon emissions compared to metal piping, aligning with the growing demand for sustainable data center solutions.

GF's commitment to innovation, quality, and customer support is exemplified by its development of advanced solutions like LiquidCore and its pioneering work in infrared welding technology. This non-contact welding method ensures the creation of clean, homogeneous joints with exceptional strength and reliability, further enhancing the integrity and longevity of DLC systems. With a comprehensive portfolio of high-performance polymer piping solutions, a global presence, and a wealth of expertise in mission-critical applications, GF is uniquely positioned to partner with data center operators in the design, construction, and operation of their DLC systems. By choosing GF, customers gain access to a reliable partner dedicated to delivering sustainable, efficient, and cost-effective solutions that meet the evolving challenges of the data center industry.

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