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MODULAR TECHNOLOGY COOLING SYSTEM FOR “CLOUD SCALE”: DESIGN & DELIVERY OF LIQUID TO RACK DISTRIBUTION SYSTEMS

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Executive Summary

Liquid cooling has long supported specialized IT applications, but the rise of high-density compute for “AI Factories” has pushed the industry into an era of cloud-scale deployments. Unlike traditional, bespoke liquid distribution systems, today’s projects require modular, adaptable, and repeatable Technology Cooling Systems (TCS) capable of scaling from tens to hundreds of megawatts. These deployments face evolving requirements—uncertain rack power densities, shifting ΔT ranges, and fluid quality standards—that challenge conventional design and delivery practices.

This white paper provides guidance on the design and deployment of modular water-based TCS systems, focusing on constructability, maintainability, reliability, and digital design tools such as BIM-enabled delivery. Modularization enhances cleanliness, quality control, and supply chain resilience, while enabling global scale deployments with reduced risk. To ensure broad relevance, this work has been developed not by a handful of authors, but through a process of global crowd-sourcing: multiple review sessions, open feedback loops, and contributions from a broad spectrum of industry experts across colocation providers, hyperscalers, OEMs, contractors, and standards bodies. This open development approach embodies the spirit of the OCP community by ensuring the framework reflects the needs and insights of the entire ecosystem.

Aligned with the **OCP Tenets**, this paper emphasizes:

- **Openness:** Crowd-sourced input, shared specifications, and transparent design frameworks.
- **Efficiency:** Optimized flow, chemistry, and energy management for resource-conscious operation.
- **Impact:** Reduced deployment risks, improved uptime, and lower total cost of ownership.
- **Scale:** Repeatable modular systems enabling rapid global deployment.
- **Sustainability:** Cleaner fabrication, longer lifecycle systems, and circular design practices that reduce environmental impact.

In summary, modular TCS design and delivery—anchored by OCP’s principles and strengthened by global, crowd-sourced collaboration—provides a transparent, scalable, and sustainable path for liquid cooling at cloud scale. This inclusive and open approach ensures the industry can evolve rapidly while reducing risk and maximizing long-term value.

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1. Introduction

Open Compute Project (OCP) Advanced Cooling Facilities (ACF) has been developing guidance around deployment of liquid cooled IT since 2020. Previous guidance includes:

- *Guidelines for Connection of Liquid Cooled ITE to Data Center Facilities*
- *Data Center Liquid Distribution Guidance & Reference Designs*
- *Guidelines for Using Propylene Glycol-Based Heat Transfer Fluids in Single-Phase Cold Plate-Based Liquid Cooled Racks*
- *Guidelines for Using Water-Based Transfer Fluids in Single-Phase Cold Plate Based Liquid-Cooled Racks*
- *Cold Plate Cooling Loop Requirements. Rev. 2*

This whitepaper draws much guidance from those previous ACF papers but specifically focuses on the unique and evolving requirements of “Technology Cooling System” (TCS) as well as the challenge of deployment at “Cloud-Scale” - global deployments of ~10MW to 300+ MW. OCP Guidance from “Advanced Cooling Solution” subprojects (Door HX, Cold Plate, Immersion) as well as guidance from ASHRAE TC 9.9 is also included.

The escalating demand for liquid cooled IT is driving the need for multi-megawatt (MW) deployments, where traditional job-site construction methodologies will not suffice. Modular deployment of pipe systems using off-site construction and DfMA (design for manufacture & assembly) concepts is essential to meet construction as well as adaptability requirements, while lowering the risk.

2. Compliance with Open Compute Project Tenets

2.1. Openness

The concepts around modular design, fabrication, and delivery of the “technology cooling system” are all open concepts, achievable by open technologies, accessible globally. Where example product images are displayed to illustrate these concepts, alternative products meeting performance requirements are equally recommended. Much of the guidance herein on “open” connection methodologies has been previously addressed in OCP Whitepapers.

2.2. Efficiency

Modularity and offsite manufacture of systems has been demonstrated throughout the data center industry as a method to improve efficiency in manufacturing and reducing waste. Prefabrication lends itself to higher quality, at a lower build cost, and higher throughput rate.

2.3. Impact

Your contribution should have a transformative impact on the industry by introducing new technology, accelerating time-to-market, or enabling technology through global supply chains. Impact is amplified when new technologies are made accessible to many customers worldwide. Examples include widely adopted specifications or more specifically, open security features that establish and verify product trust. Ensure your contribution creates meaningful positive impact within the OCP ecosystem.

2.4. Scale

Design your contribution for easy implementation and deployment at any scale, with minimal intervention. Aim to create additive solutions where minimal usage or instances can be deployed and incrementally scaled as needed to effectively address the entire problem. Provide all necessary tools and supporting documentation, such as installation guides, initialization processes, configuration information, and details on obtaining service support. Include features like simple manual and automated maintenance, remote management, upgradability, and error reporting. Management tools should be open-sourced and/or made available to adopters.

2.5. Sustainability

Modular design & delivery of the TCS addresses both embodied carbon and Scope 3 GHG emissions related to the manufacturing and construction of materials and facilities. Modular design and fabrication can significantly reduce embodied carbons via optimization of source

material, reducing transportation related activities, reducing waste, and enabling more efficient manufacturing. From a construction standpoint, it can also reduce material handling, waste and transport, and construction related activities. Modular standardized equipment can also optimize use, maintenance, and repair, which also reduces the embodied carbon footprint.

Modular deployment of the TCS simplifies adapted reuse of existing facilities, enabling migration from air cooled to liquid cooled IT, extending lifespan, advancing performance, minimizing obsolescence and replacement. As for Scope 3 GHG emissions, modular designs are having a positive impact on operational energy usage, and/or operational water use.

3. Modular TCS @ Cloud-Scale - Design & Delivery

3.1 Key Benefits for Modular TCS Design & Delivery

- **Adaptability to meet ΔT , KW / Rack Changes:** Changes in IT equipment power density and thermal requirements (e.g., ΔT) will impact loop size requirements over the life of the data center. Adding, removing, and reusing pipe system modules addresses demands for adaptation and optimization of facility performance and resources.
- **Pipe Cleanliness:** TCS systems require much higher levels of cleanliness than Facility Water Systems (FWS), with filtration to maintain contamination below 25 μ m becoming more common. As discussed in [Appendix G](#), achieving this level of cleanliness requires extensive consideration in design, fabrication, construction and commissioning. Off-site fabrication of TCS modules enables greater cleanliness and more sustainable practices in manufacturing and delivery of pipe systems. As discussed in [Appendix C](#), combining 25 μ m, or even 50 μ m, inline filtration with side-stream filtration (e.g. <5 μ m) is one method to achieve and maintain filtration requirements.
- **Sustainability:** Offsite manufacturing has certain sustainability benefits, and modular design and delivery can support circularity practices. As data center requirements evolve, the ability to add or reuse TCS modules will become an opportunity as ΔT and rack density evolves.
- **Supply Chain:** Growing demand for liquid cooled IT is causing global supply chain issues. Inventory management and regional manufacturing hubs help address these challenges.
- **Risk/Defect Reduction:** Offsite repetitive manufacturing reduces failures and improves testing and quality control.
- **Jobsite Skilled Labor Hours:** Modular solutions lower the number of skilled labor hours needed on the jobsite.

3.2 Requirements for Modularity in TCS Pipe Systems

Effective modular deployment of Technology Cooling System (TCS) piping involves considerations beyond modularity, including factors such as design, constructability, and reliability. Important design aspects include adaptable system architecture, connection interfaces, and provisions for pre-commissioning activities like flushing and testing. Constructability can be improved through offsite prefabrication, simplified alignment, and the use of BIM-enabled DfMA methodologies. Reliability is supported by quality control measures, visual inspections, and detailed procedures that help maintain operations and mitigate risks related to leaks, thermal performance, or material failures—thereby supporting maintainability and continued service.

System design

Modular systems should be designed to minimize joint count—especially avoiding high-risk jobsite connections. Fewer joints mean fewer failure points, improving system reliability and lowering ongoing operations and maintenance (O&M) costs. Collectively, these benefits reduce total cost of ownership.

As addressed in detail in OCP WP on “*Guidelines for Connection of Liquid Cooled ITE to Data Center Facility Systems*”, selection of connection method should include:

- **Standardized Connection Methods:** Using repeatable, industry-standard joints that maintain mechanical integrity across all sections. For threaded connections, BSPP is identified as a global standard used in data centers.
- **Alignment Tolerance:** Incorporating piping designs that consider alignment tolerance requirements and include provisions to correct or allow for minor alignment deviations during assembly without compromising joint integrity.
- **Vibration, building movement and seismic stress:** Vibration, building movement and seismic stress are key considerations, especially in “cloud scale” facilities. Design strategies such as using vibration dampers, flexible couplings, and seismic bracing help absorb mechanical shocks and prevent joint failures, enhancing overall system resilience.
- **Connection Method Reliability Data:** Cloud-scale data centers can have 20,000 - 40,000 pipe system connections or more. As detailed in Appendix A, integrating FMEA with connection reliability analysis forms the basis for reliable, low-risk operation.

Design Flexibility for Future Adaptation

A key advantage of modular TCS is the ability to adapt to changing design, business and operational needs. Effective design allows for:

- **Scalability:** Adding or removing modules without major system redesign, enabling phasing of expansion, as required.
- **Multi-Configuration Compatibility:** Supporting diverse fluid routes or additional cooling capacity through standardized module integration.
- **Service Access:** Designing modules with clear, repeatable access points for inspection and modification, reducing operational downtime during upgrades.

3.2.2 Constructability (Additional content in Appendix F)

Thermal Movement Management

Pipe systems must account for significant temperature variations, from jobsite conditions (15–20 °C) to potential peaks above 70 °C. Using materials with low thermal expansion and connections that tolerate movement prevents stress, leaks, and alignment issues, ensuring long-term stability and adaptability. Use of connection methods that accommodate movement and mitigate associated stresses is key as well.

Easy Alignment of Connection Methods

A modular pipe system needs simple, reliable connections between pipes and components, even in varied conditions. Prefab installation becomes difficult with methods that demand exact alignment. Ensuring easy alignment speeds up both installation and maintenance. Standardized connections, precise parts, and built-in adjustment features help engineers align pipes quickly during assembly.

Movement Accommodation

In addition to thermal movement, pipe systems often encounter other forms of movement, including vibration, settling, and seismic activities. Designing modular pipe systems that can accommodate these movements without compromising their integrity is essential. Bolted flange connections require perfect alignment for connection and minimal pipe movement to enable

maintenance and reconnection. Pipe systems should incorporate flexible joints, expansion loops, and vibration dampeners to absorb and distribute movement forces. By allowing controlled movement within the system, engineers can prevent stress accumulation, leaks, and structural damage. Movement accommodation enhances the durability of the pipe system and simplifies maintenance, promotes circularity, and prolongs the system's life cycle. (see Figure 1 from OCP WP on Connection Methodology).

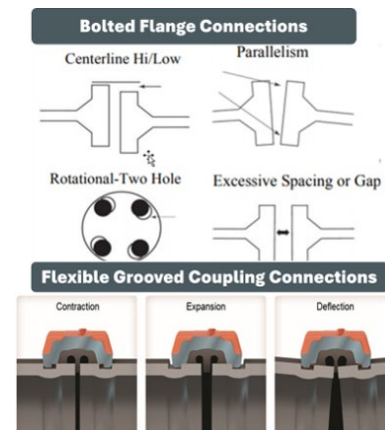


Figure 1: Alignment & Movement Considerations

BIM Enablement of DfMA

The concept of DfMA - Design for Manufacture & Assembly – is the foundation of a modular TCS design and delivery. Success in DfMA in construction requires that all components be modeled in a constructible, digital format, with sufficient accuracy for fabrication but constrained level of file size to support evaluation using common laptop processors. BIM (Building Information Model) is the language of pipe system modularity. BIM content LoD (Level of Development) 350+ is the starting point of modular design. Having vendors provide all content in BIM LoD 350+ greatly simplifies the speed, success, and reduces the cost of DfMA.

3.3 Reliability Considerations (Greater detail in Appendix A)

Reliability of Connection Methods - Verified reliability of connection methods is crucial for both initial installation and subsequent inspections. OCP whitepaper on “*Guidelines for Connection of Liquid Cooled ITE To Data Center Facility Systems*” reviews common pipe system connection methodologies (flange, weld, thread, grooved coupling, fused, crimped) and evaluates each method for ability to verify connection reliability. The “*OCP Guidelines for Connection Methods*” whitepaper also discusses use of leak detection, leak protection, and FMEA (failure mode effect and analysis) to consider when verification of reliability is not available or practical.

Auditability, Traceability - TCS connection installation verification should be auditable and traceable back to the performing inspector and/or installer.

Brittle Fracture Prevention - Avoid materials and connection methods subject to brittle fracture due to aging, thermal conditions, chemistry, or stress.

TCS Water-Based Fluid Requirements

Guidance for TCS fluids is detailed in OCP and ASHRAE TC 9.9 documents, including:

- *OCP Guidelines for Using Water-Based Heat Transfer Fluids in Single-Phase Cold Plate-Based Liquid Cooled Racks*
- *OCP Cold Plate Requirements, Rev 2*
- *ASHRAE TC 9.9 WP on Water-Cooled Servers, Common Designs, Components, and Processes*

Key fluid-related considerations for pipe system design include:

- **Chemical Interaction:** Evaluate chemical compatibility of glycol blends and inhibitors with all wetted materials to prevent embrittlement, corrosion and generation of biofilm.
- **Specific Heat Impact:** Water's high specific heat provides superior cooling capacity. Glycol additives reduce specific heat (<10%), decreasing system capacity proportionally.
- **Temperature Range:** Fluid temperature varies by application. Rear door heat exchangers operate cooler than direct liquid-to-chip systems, where chip case temperatures (~90 °C) necessitate TCS fluid design temperatures to 70+ °C.
- **Filtration:** Microchannel heat exchangers require fine filtration ($\leq 25 \mu\text{m}$). Pipe materials prone to corrosion (e.g., carbon steel) are generally avoided. SOPs and MOPs must prevent contamination during maintenance.

As discussed in Appendix G, offsite fabrication with clean delivery and flushing reduces onsite cleaning requirements, improves sustainability, and ensures removal of air, particles, and chemical residues.

Filtration below 50 μm – As discussed in Appendix D, filtration requirements also vary with application. As addressed in the OCP WP on use of PG fluids in cold plate applications, “microchannel heat exchangers” often require finer filtration to avoid clogging, with requirements

for 25µm filtration becoming more common. Pipe materials that contribute corrosion products (i.e., carbon steel) require careful consideration and are typically avoided. Maintenance procedures (MOPs, SOPs) need to be defined to ensure standard maintenance and operation does not introduce contamination.

Requirement	Door HX	Liquid To Chip
T max	< 100° F / 37° C	160° F / 70° C
T min	~ 68° F / 20° C	~ 68° F / 20° C
Design Δ Range	32° F / 17° C	90° F / 50° C
P max (operation)	100 PSI, 6.5 Bar	60 PSI, 4 Bar
25µ Filtration	Maybe	Yes
Common Pipe Types	Carbon Steel, Stainless Steel, Copper, PPR, CPVC	Stainless, 304 or 316 Sched 5 or Sched 10
Yellow Highlights => Significant Design Concern in Pipe Material Selection		
Table 1 Liquid To Rack Pipe Design Considerations		

Offsite fabrication facilities are more proficient at maintaining a clean environment with higher levels of sustainability control than most job sites, including management of flushing agents. Offsite flushing and “clean delivery” processes can reduce the need for extensive cleaning on jobsite and optimize sustainability of the flushing process. Pipe cleaning and flushing process should ensure removal of all air, dirt particles, cleaning chemicals and any waste products from welds and fusion connections.

3.5 TCS Flow Considerations

Flow Velocity Limits: Flow velocity affects both heat transfer and energy use. While high-performance systems may exceed 3 m/s (10 ft/s), efficiency demands lower velocities since head loss and energy consumption rise sharply with flow rate.

Note: ASHRAE 90.1 exempts "process loads" from building energy code velocity limits, but local jurisdictions may impose restrictions. Further ASHRAE guidance is forthcoming.

Fluid Characteristics and Erosion Risk: Besides velocity, factors like particulate content, turbulence, corrosive chemistry, and air or gas entrainment also affect erosion risk. Following TCS fluid quality standards helps reduce these risks.

3.6 TCS Pipe Selection Considerations

- TCS Fluid Quality Compatibility
- Thermal performance range (20 °C-70 °C)
- Thermal movement, (20 °C-70 °C)
- Embrittlement
- Flow Area, Cooling Capacity
- Carbon Footprint, Full Scope
- Cost - Raw cost, Total Installed Cost, Total Cost of Ownership

TCS Fluid Quality Compatibility - Selecting clean pipe materials is essential for Technology Cooling Systems (TCS). Passivating after welding or hot work reduces corrosion. Minimizing dead-legs and cavities is also crucial. Above all, proper fluid chemistry is vital to prevent biofilm growth and corrosion.

Connection types matter for system cleanliness. Sanitary tri-clamp fittings allow for easy cleaning and eliminate crevices. For grooved couplings, use a flush, non-intrusive gasket design to minimize particulates and biofilm. Bolted flanges, if misaligned or poorly sealed, can create stagnant zones that promote biofilm and debris buildup.

Thermal performance range (20 °C to 70 °C) – TCS

proximity to chip temperatures creates a broad temperature band for design consideration.

Temperatures at construction are typically around 20 °C/68 °F. Chip shutdown temperatures can reach >77 °C / 170 °F, creating the potential for TCS fluid temperatures as high as 70 °C / 160 °F. As shown in Figure 2, non-metallic pipe materials experience significant reductions in mechanical strength at higher temperatures, necessitating additional structural support or increased pipe wall thickness to maintain integrity.

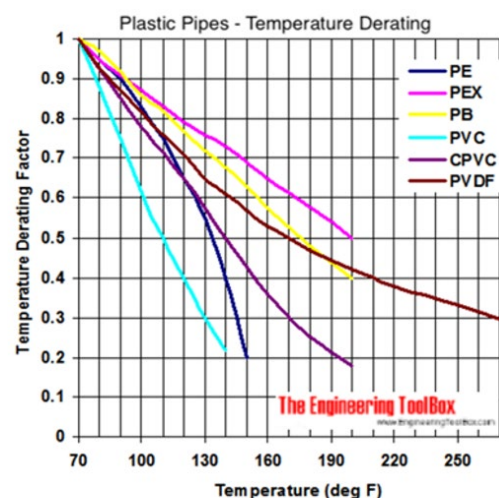


Figure 2 Temperature Derating

Thermal movement, (20°C to 70°C) – Liquid to Chip Cooling, driven by AI workloads, presents new challenges in thermal movement. Chip temperatures can exceed 70°C. While normal operating TCS fluid temperatures may be around 35°C, various conditions can cause thermal spikes, pushing TCS fluid temperatures up to 70°C. This can result in >50°C of thermal movement and frequent thermal cycling. As the thermal range of the TCS increases, thermal movement becomes a key consideration in selection of pipe material. (See Figure 3). Pipe system mounting and installation needs to accommodate the full range of motion. Operational modularity and circularity are greatly simplified with minimal thermal movement.

Movement Stress Considerations for Pipe

Connections - Thermal movement can cause pipe connections to become stress points, impacting both maintenance and long-term reliability. Connection methods not designed to accommodate thermal cycling, or significant thermal movement may require additional expansion components and routine inspection of gaskets and torque settings.

Thermal expansion can cause gasket compress in flanges and Tri-Clamp. In the case of flanges, bolt torque management is recommended. Likewise, with Tri-clamp periodic inspection is recommended, tightening as necessary. Grooved couplings can be designed for “life of the pipe” performance, where no inspections or maintenance is required after proper installation is verified, to include thermal movement.

Embrittlement – A variety of factors can contribute to materials becoming brittle. Brittle materials are subject to sudden catastrophic failure at conditions below design strength. High temperature, chemistry, stress, and age are factors that can lead to embrittlement of some nonmetal pipe materials. Weld defects can also create areas of embrittlement. Manufacturers should provide data addressing the potential of embrittlement.

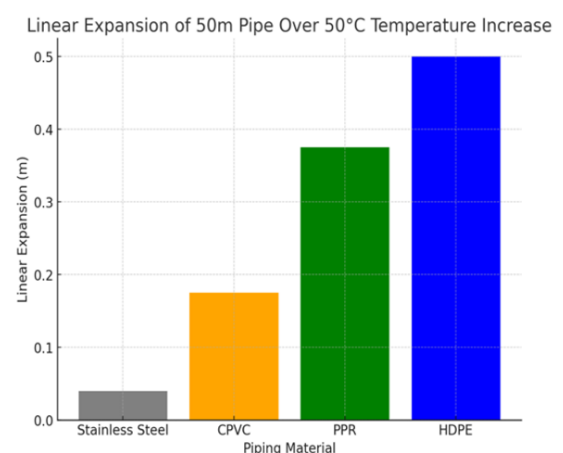


Figure 3: Thermal Movement Comparisons, 20C to 70C

Flow Area, Cooling Capacity – Pipe systems are often compared by nominal pipe size (NPS), with NPS 4 and NPS 6 common sizes considered for TCS systems. However, the pipe area available for flow is determined by the internal diameter (ID).

Non-metallic pipes require significantly thicker walls as pressure ratings drop significantly at temperatures above 40°C, resulting in reduced internal diameter (flow areas) for given external pipe diameter. In the example shown in Figure 3.5.2, the heat carrying capacity of different pipe materials can be compared using a pipe comparison tool. PPR (SDR 11) and CPVC (SDR 11) have smaller internal diameters and reduced capacity due to wall thickness of non-metals.

(Note: Pressure rating and SDR (Standard Dimension Ratio) of non-metal pipe at 70°C should be verified with vendor.)

[Pipe Material Capacity Comparison Tool](#)

PIPE COMPARISON TOOL

Enter your information into the indicated areas to populate results.

HEAT TRANSFER FLUID: Propylene Glycol 25%
 ΔT (°C): 10
 18 °F
 VELOCITY (M/S): 2.5
 8.20 (ft/s)
 SPECIFIC HEAT (KJ/KG °C): 1.030
 DENSITY (KG/LITER): 1.030

PIPE PROPERTIES	DENSITY (KG/CLL M)	LINEAR COEFFICIENTS OF EXPANSION 10-6 IN /IN °F	LINEAR EXPANSION COMPARISON TO CARBON STEEL
Stainless Steel - Stainless Steel Schedule 5	8030.06	9.90	1.5
CPVC Chlorinated Polyvinyl Chloride - SDR 11	1559.24	44.00	6.8
PP Polypropylene - SDR 11	909.85	50.30	7.7

PIPE SIZE (IN)	DN (MM)	MATERIAL	SCHEDULE	CROSS SEC AREA (SQ. IN)	MAX KW	"DRY" PIPE WT PER FOOT (LB/FT)	"WET" PIPE & FLUID WT PER FOOT (LB/FT)	CROSS SEC AREA (SQ. IN)	MAX KW	% KW COMPARISON TO STAINLESS STEEL SCHEDULE 5	"DRY" PIPE WT PER FOOT (LB/FT)	"WET" PIPE & FLUID WT PER FOOT (LB/FT)	CROSS SEC AREA (SQ. IN)	MAX KW	% KW COMPARISON TO STAINLESS STEEL SCHEDULE 5	"DRY" PIPE WT PER FOOT (LB/FT)	"WET" PIPE & FLUID WT PER FOOT (LB/FT)
6	150	Stainless Steel	Stainless Steel Schedule 5	32.24	2079.19	7.77	22.19	23.08	1488.48	72%	7.70	18.02	23.08	1488.48	72%	4.49	14.82

6" / DN 150 Pipe Capacities: Stainless (Sched 5) ~ 2079 KW; CPVC, PPR (SDR 11) ~ 1488 KW

Figure 4: Flow Area Comparison vs Pipe Material - Stainless Steel, CPVC, PPR

Head-Loss is the reduction in the total energy (or pressure) of a fluid as it moves through a piping system due to friction and other resistance. A detailed evaluation of head-loss should be performed by a licensed engineer as part of the evaluation of pump and energy requirements. Figure 3.5.3 provides an example of the impact of pipe size on head-loss and lists the other factors in head loss (Darcy-Weisbach) calculation.

Carbon Footprint (Embedded Carbon - including recycled content) – The increasing focus on reducing carbon footprints is influencing the selection of construction materials, with a particular emphasis on evaluating the environmental impact of different types of piping materials. A major hurdle in this process is the difficulty of obtaining comparable data for the carbon footprint of metallic and non-metallic pipes, especially when considering the use of recycled materials.

Recycling is a common practice in the production of metallic construction materials, including pipes. The construction industry has made significant advancements in recycling metal waste. In contrast, the use of recycled material in non-metallic pipes is very uncommon. Stainless steel pipes typically have a high content of recycled stainless steel. Non-metallic pipe waste has limited use in TCS products that require exceptional cleanliness and performance at 70C.

When assessing the full scope of a product's carbon footprint, it's crucial to consider the impact of material reuse. To demonstrate this point, consider an example comparing Environmental Product Declarations (EPDs) for three types of pipes – stainless steel, HDPE (High-Density Polyethylene), and PPR (Polypropylene Random Copolymer). These pipes, all with the same internal diameter, were analyzed in terms of their raw material CO₂ footprint, as well as how their carbon footprint changes when recycled content is included. This comparison underscores how recycled content significantly influences the carbon footprint of pipes.

NPS	Internal Diameter used for comparisons (mm)			304L Stainless OD= 164.3mm		SDR11 HDPE OD=200mm		PPR SDR 11 OD=200mm	
	Stainless Sched 5	HDPE	PPR	CO2 A1-A3 (Kg/lm)	CO2 Full Scope (Kg/lm)	CO2 A1-A3 (Kg/lm)	CO2 Full Scope (Kg/lm)	CO2 A1-A3 (Kg/lm)	CO2 Full Scope (Kg/lm)
6"	164.3mm	163.6mm	163.6mm	30.78	16.47	32.54	32.97	24.89	24.89
Note: Comparisons based on equivalent flow areas (internal diameters) to Sched 5 Stainless Steel pipe Yellow = Carbon Content, Raw Material Green = Carbon Content including recycled content.									
Table 4: Full Scope CO2 Footprint Stainless Steel vs HDPE vs PPR									

(Note - comparison is simply to demonstrate that carbon footprint can vary significantly with recycled content and that pipes should be compared by internal diameter.

Actual carbon footprint will vary with product and manufacturer.)

Cost - Raw Pipe Cost vs Total Installed Cost vs Total Cost of Ownership

Cost is always a key consideration in any project. In comparing pipe costs, there are several levels of consideration: raw pipe material cost, total installed cost, and total cost of ownership (TCO). TCO is the most holistic evaluation, but often difficult to calculate.

Raw Pipe Cost is the easiest to measure, as the cost of pipe is widely available. Non-metallic pipe such as CPVC, PPR, HDPE is generally lower cost versus stainless steel pipe. For diameters over three inches, stainless steel is substantially lower cost than copper pipe.

Total Installed Cost includes installation costs, labor hours, and ability to support off-site manufacture. Total Installed Cost in offsite modular delivery is greatly influenced by thermal movement concerns, integration with branch line assemblies, and simplification of connection methodology. Total Installed cost considerations include:

- Cost of pipe
- Labor for pipe, branch lines, and connection methods.
- Impact of thermal movement on need for job-site adaptation and design
- Commissioning, installation verification, leak detection, and protection requirements

Total Cost of Ownership includes maintenance and adaptation costs over the life of the data center. Pipe movement and related stress at connection points can significantly increase MTTR (mean time to repair) and limit the ability to adapt the pipe system. The ability to conduct maintenance and/or adapt pipe systems during the life of the data center can be a significant cost variance.

3.7 Loop & Branch Line Alignment to Electrical Capacity

A consideration on loop sizing is alignment with electrical bus capacity, to create (or alternately avoid) matches in maintainability and failure mode impact. Electrical bus capacity determines the maximum amount of heat generated by ITE. Amongst the many variables needed to consider when designing the cooling solutions, it is also essential to understand the intended rack density and number of racks, the net IT kW change to the room, and its heat rejection ratio to the cooling liquid. Liquid cooling installations can be delivered with a variety of coordinated

liquid and air-cooling systems as many liquid cooling solutions only capture 70-80 percent of the total IT system heat. Heat not captured by the liquid will require computer room air-handlers (CRAH), fan walls or other air-cooling systems.

Different cooling methods have different levels of heat captured by the liquid. Whereas immersion cooling captures almost all the IT heat into the liquid, but there will still be ambient heat losses from the immersion cooling system to be dealt with by a space air cooling scheme. A typical cold plate cooling system may capture 70%-80% of the ITE heat. Correspondingly, the TCS system capacity requirements for cold-plate could be 80% of the associated electrical load, but TCS capacity requirements for immersion would be closer to 100%.

There are a variety of electrical distribution limitations that may impact selection of optimum cooling loop sizing, including maximum busway capacity and Power Distribution Unit Capacity (PDU). Maximum capacity of the electrical system (PDU, UPS, and Busway) is a key consideration on maximum sizing of TCS systems.

Combinations of cooling methodologies will be necessary in facilities supporting liquid cooled IT. While it is likely that percentage of heat capture by liquid will increase as densities increase, there will always be some component of heat escaping to the data center environment and air cooling of the IT environment will still be a significant consideration even in a data center filled with “liquid cooled” IT.

For example, cold plate partnered with a door heat exchanger could capture close to 100% of the IT heat into the TCS. However, even low percentages of heat escape can be considerable as IT rack heat density grows to 50 KW and beyond, requiring additional room and row heat capture from the air. There will always be some requirement for air cooling and humidity control in data centers to capture the heat and moisture not fully transported by the liquid systems.

Having cooling capacity in excess of electrical capacity is typically an example of misalignment of resources. CDU capacity in excess of electrical busway capacity and Power Distribution Units (PDUs) capacity has minimal benefit except where deliberately included to provide redundancy or concurrent maintainability.

3.8 Branch Line Considerations - Connecting ITE to Pipe Header

Standardized branch line assemblies are key to procedure and performance simplification. Key components include isolation valve, flex line, flow control, and connection to rack:

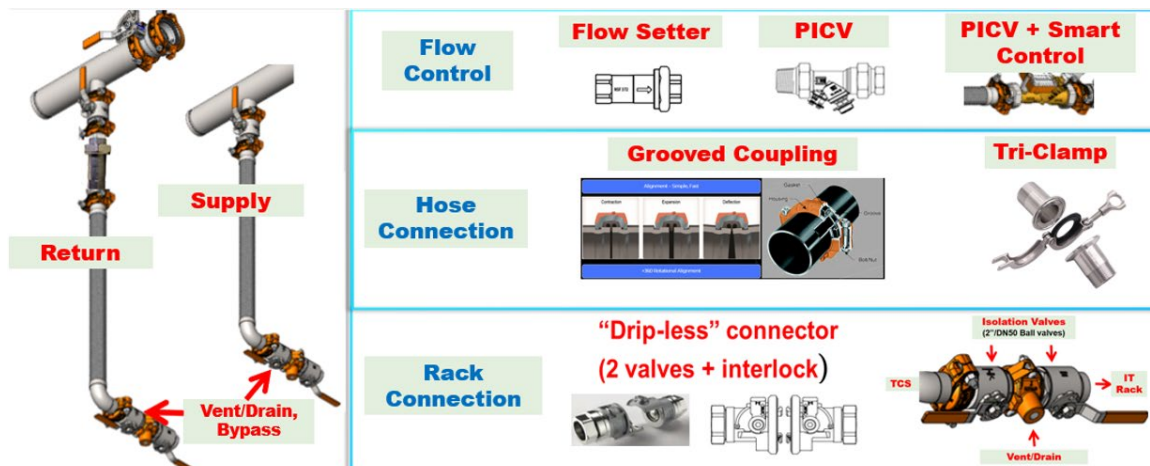


Figure 5: Branch Line Components

- **Header Isolation:** Isolation valve at the header allows isolation/removal of branch line. Automatic isolation actuation option may be a consideration in connection with leak detection.
- **Flow Control valve:** Recommended to improve flow response to address variations in pressure and demand. Maintaining specified flow rates is beneficial to both addressing the heat load and the long-term viability of the cold plate. Underflow could lead to insufficient heat removal, which could damage the IT equipment, while overflow could, over time, lead to erosion of the cold plate channels. Flow control options and design considerations are discussed in greater detail in **Appendix D: Flow Control Considerations**
- **Flex Line :** For typical branch line flow rates (7.5 fps, 2.3 m/s) and $\Delta T = 18\text{ }^{\circ}\text{F}/10\text{ }^{\circ}\text{C}$, a 1"/DN25 branch line can transport ~ 56KW, a 2" (DN50) line can transport ~ 214KW.
- **IT Rack Branch-line Isolation:** Use of double-Isolation valves or drip free connections at the connection point to the IT equipment prevents the need to drain the branch line when the IT rack is separated from the TCS.

- **Branch Line Vent/Drain Option:** Addition of vent/drain ports in the IT rack connection (Figure 6) enables the process of purging contamination and venting air when adding IT racks to the TCS. During design, operation and maintenance considerations/input is needed to ensure work areas over critical IT hardware and mission critical MEP infrastructure are carefully coordinated. (see Appendix G: Commissioning)

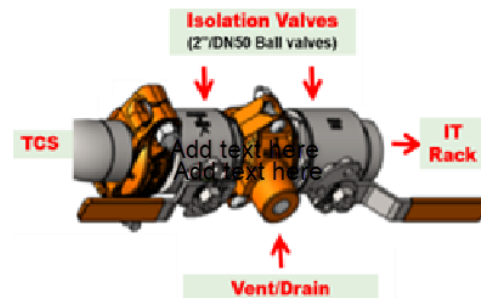


Figure 6: Two Ball Valves + Vent / Drain

As will be discussed further in Appendix G, ensuring cleanliness and leak prevention in the TCS necessitates the use of pre-assembled and pressure-tested branch lines equipped with standardized connection methods to IT systems. Achieving stringent filtration requirements, such as 25 microns, is challenging with conventional job-site construction, as materials like pipe tape and pipe dope are prohibited within TCS systems. An integrated design approach for headers and branch lines significantly mitigates the risk of galvanic corrosion by eliminating the need for on-site evaluation of individual components. Furthermore, modular, pretested branch lines simplify flow rate and heat dissipation (kW) capacity validation, enhancing system reliability and performance.

IT Rack Connection Considerations: Disconnection of a liquid cooled IT rack is an infrequent operation, typically only performed when a major refresh of IT is required (3-7 years or longer). The process of removing a liquid cooled IT rack should be clearly documented in procedure (i.e. MOP) and will include multiple steps. Typical steps include isolation of the IT rack supply and return lines, and either draining in place or rolling the full IT rack out to a drain location.

“Open” IT rack connection methods include:

- **OCP Large Quick Connector:** The OCP [Large Quick Connector Specification](#) is a global standard developed within the OCP for 1”/DN25 connection with “drip-less” characteristics.

- **Double- Isolation valve + grooved coupling connection.** Use of isolation valves + grooved coupling is another “open” method that provides the ability to isolate both the branch line and IT rack during connection and disconnection. A clearly defined procedure (MOP/SOP) is recommended. There may be a small amount of fluid (<100ml) released during separation if draining prior to separation does occur. In addition to being an “open” (non-proprietary) method of connection, double ball valves enable use of vent/drain/bypass connections to address commissioning and onboarding challenges as well as flow stabilization.

Proprietary IT rack connection methods include:

- **“Drip less” Interlocked connectors.** Proprietary connection methods featuring double-valve isolation and safety interlocks, designed to minimize water entrainment between the valves and prevent separation of connections unless both valves are shut. Considerations for venting entrained air and cleaning connection surfaces should be considered with drip-less connectors that do not have vent/drain.

Thread Connection - Where threaded connections are used, BSPP is the recommended thread connection per OCP “Connection Methods” WP. However, use of thread connections for disconnection / reconnection of IT racks in the field is often discouraged due to the increased risk of installation errors, and restrictions on use of lubricants and pipe tape. The general recommendation is that threaded connections be limited to “factory” or shop installation, with mechanical connections (tri-clamp, couplings, drip-less connectors) used for repeated disconnection and reconnection.

Grooved Coupling Connections - *Grooved* couplings are recognized and specified by a variety of organizations as a reliable method for cooling water applications to provide a simple connection method that can be verified with measured reliability. As a reference, reliable operation of a hyperscale data center with 20,000 connections over 25 years requires an MTBF greater than 4.4 billion hours. Movement accommodation on header sections can be accommodated by the use of flexible couplings. **Gasket selection for TCS grooved applications is a critical consideration.** Gasket should be pressure responsive, capable of full

vacuum service, and comprised of a material compatible with the fluid media (i.e. PG25). To prevent issues with particulate or biofilm generation a non-intrusive center leg geometry that seats flush on the outside diameter (OD) of the pipe and prevents the housing from contact with the fluid is recommended. Gasket lubricants should be easily flushed with no residue (i.e. PG 25 or soap lubricants as recommended by the manufacturer).

Tri-Clamp Connections (DIN-32676 specification)- Tri-clamp connections, commonly used in the food and beverage and biopharmaceutical industries, are a consideration for some TCS applications. As with grooved couplings, a recommended MTBF >5 billion hours is adequate to support most long-term reliability requirements of mission critical applications. Tri-clamps follow hygienic design principles to minimize crevices and reduce susceptibility to trapped particulates and formation of biofilms. However, Tri-clamps may be affected by thermal movement and bending moments and periodic inspection is often recommended in TCS applications.

IT Rack Connection Reliability Considerations The connection between the IT rack and the branch line is one of the most critical connection points in the data center. Reliability of connection methods is discussed in OCP White Paper on Connection Guidance as well as Appendix A of this document. Installation and removal recommendations for IT Racks is addressed in greater detail in Appendix G.

Branch Line Sizing Considerations

Selection of branch line size for a large-scale data center is a complex discussion with considerations of capacity, pressure drop & balancing, connection method and supply chain. Demand for high density IT racks in excess of 100 KW is escalating. The trade-off of large capacity 2"/DN50 supply lines versus multiple 1"/DN25 supply lines is a common discussion.

- **Capacity:** A 1"/DN25 branch at typical flows and temperatures can transport approximately 55 KW of heat; a 2"/DN50 branch approximately 170KW - 220KW.
- **Connection Method:** Quick connection method for 1"/DN25 branch lines is a global standard that combines simplicity, speed and reliability. "Drip-less" connectors at

2"/DN50 are proprietary. Dual ball valve solutions are not proprietary and readily available globally, but increase the need for defined procedures (see discussion in Appendix G).

- **Supply Chain:** Reduced availability of proprietary “drip less” connections supporting 2"/DN50 applications has delayed adoption. Global production is increasing and 2" connections will likely be more common.
- **Pressure drop:** Higher density IT racks require more flow. A 2"/DN50 branch line supports approximately four times the flow volume (and heat transportation) of a 1"/DN25 branch line at the same flow velocity. Correspondingly, head-loss (pressure drop) increases proportional to the square of the velocity. Using 2"/DN50 branch lines can significantly reduce head-loss and balancing issues.

4. Conclusion

The escalating demand for liquid-cooled IT systems at scale, often without clear thermal or power parameters, requires advances in design and delivery. To meet this need, liquid distribution must be adaptable, efficient, and sustainable, aligning with the OCP tenet of Efficiency.

A modular approach to Technology Cooling System (TCS) piping - including headers and branch lines - addresses these challenges by fostering adaptability and simplifying fabrication and supply chains. Off-site assembly improves cleanliness, reduces risks, and leverages economies of scale, advancing Impact and Sustainability.

Key requirements include managing thermal movement, reliable and maintainable connections, and integrating sensors, valves, and automation to maintain stable performance. Standardized methods, supported by BIM and digital delivery tools, promote Openness and reproducibility.

In conclusion, modular TCS systems designed for constructability, maintainability, reliability, and scalability support the OCP tenets of Openness, Efficiency, Impact, Scale, and Sustainability. This approach reduces risk, supports cleaner deployments, and enables scalable, environmentally responsible growth of liquid-cooled IT infrastructure.

5. Glossary

Term	Definition
Artificial Intelligence (AI)	An interdisciplinary field, usually regarded as a branch of computer science, dealing with models and systems for the performance of functions generally associated with human intelligence, such as reasoning and learning.
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers, a Global Non-Profit professional organization that develops standards and guidelines for HVAC systems.
ASME	ASME B31.9 contains rules for the piping in industrial, institutional, commercial, and public buildings, and multi-unit residences, which does not require the range of sizes, pressures, and temperatures covered in B31.1. ASME B31.9 prescribes requirements for the design, materials, fabrication, installation, inspection, examination, and testing of piping systems for building services. It includes piping systems in the building or within the property limits.
ASTM	ASTM (American Society for Testing and Materials) is a globally recognized organization that develops and publishes technical standards to ensure the quality, safety, and performance of materials, products, systems, and services. These standards are used by industries worldwide to guide manufacturing, testing, and quality control processes.
Cold Plate	A heat transfer device, often made of metal, that is in direct contact with the heat-generating component or assembly and is in contact with a coolant to facilitate heat transfer.
Computer Room Air Conditioning (CRAC)	A device used to cool the air within data centers and server rooms. CRAC units are typically larger air conditioning units that are used to constantly manage and regulate the temperature, air distribution, and humidity in a networked environment.
Computer Room Air Handler (CRAH)	Similar to CRAC, CRAH units are used to cool data centers, but they operate slightly differently. While CRAC units have compressors built into them, CRAH units use chilled water to remove heat from the air.

Concurrent Maintainability	the ability to perform maintenance without impact on operations
Coolant	A fluid used to absorb and transfer heat away from electronic components.
Coolant Distribution Units (CDUs)	A piece of equipment used in liquid cooling systems that is responsible for pumping and conditioning the coolant before it is distributed to the components being cooled.
Direct Liquid Cooling (DLC)	A method of cooling electronic components where liquid coolant is directly applied to the components.
Direct-to-Chip (D2C or DTC) Cooling	A liquid cooling method that involves circulating a coolant in direct contact with the heat-generating components, such as processors and memory modules, to efficiently absorb and transfer heat away.
Drip-less connectors	A type of pluggable liquid connector with mechanical interlocks which reduces the possibility of separation with open valves. Designs generally reduce volume of fluid between connecting valves, but does not eliminate fluid release.
EOP	Emergency Operating Procedure - specific steps used in an emergency
Facility Water System (FWS)	A liquid circuit which allows the transport of heat throughout a facility.
HPC	High-Performance Computing, often abbreviated as HPC.
HVAC	Heating, Ventilation, and Air Conditioning, often abbreviated as HVAC.
Immersion	A cooling technique that involves submerging electronic components in a dielectric fluid to absorb and transport heat.
Microchannels	Small channels or passages within a heat exchanger, cold plate, or other cooling device that increase the surface area in contact with a coolant and enhance heat transfer.

MOP	Method of Procedure - specific procedural steps used in maintenance
Redundancy	The inclusion of additional components, systems, or processes to ensure continued operation in the event of a failure or fault.
Reliability	The ability of a system, component, or piece of equipment to perform its designated function without failure or degradation under specified conditions over a specified period of time.
SOP	Standard Operating Procedure - specific steps used in normal operation
Technology Cooling System (TCS)	A closed liquid circuit which allows the transfer of heat from liquid cooled IT to the FWS.
Total cost of ownership (TCO)	Total Cost of Ownership (TCO) is a financial estimate designed to help consumers and enterprise managers assess direct and indirect costs related to the purchase of any capital investment, such as (but not limited to) IT hardware or equipment.
Viscosity	A measure of a fluid's resistance to flow, which involves its resistance to deformation under the influence of a shear force.

6. References

OCP White Papers

- OCP Guidelines For Connection of Liquid Cooled ITE To Data Center Facility Systems
- [OCP WP Guidelines for Using PG Based Heat Transfer Fluids in Single Phase Cold Plate Based Liquid Cooled Racks](#)
- OCP Data Center Liquid Distribution Guidance & Reference Designs
- [OCP Colo Facility Guidelines for OCP Racks](#)
- [OCP Ready™ Colo Site Assessment](#)
- OCP Guidelines For Pre-Commission Preparation Of Tcs Row Manifolds In Liquid Cooled Data Centers

Other Industry WPs and Design Tools

- [Weld Defects – Causes, Consequences, & Prevention February 15, 2016](#)
- [Weld Defects-Their Causes and How to Correct Them. Handbook Weld Defects ESAB](#)
- [How to Prevent Weld Failure](#) - <http://www.gowelding.com/weld/failure/failure.htm>
- [Welder Identification Requirements, Eng-Tips.com](#)
- [American Society for Quality - FAILURE MODE AND EFFECTS ANALYSIS \(FMEA\)](#)
- Data Center ITE Refresh Cycle – <https://www.techrepublic.com/article/ten-tips-for-planning-a-data-center-hardware-refresh/>
- Grooved Coupling/Fitting System Reliability, Availability, Maintainability Analysis Report.” Alion Science and Technology Corporation System Reliability Center, January 2012
- Accommodating Deflection, Building Creep and Settlement, Victaulic White Paper 01, Larry Thau, 2009
- Design Data – Vibration Attenuation Characteristics Publication 26.04, NASA Johnson Space Center
- Accommodating Thermal Expansion Piping Movement, Victaulic White Paper 02
- [The Engineering Toolbox](#)
- plasticpipefailure.com/cpvc-problems#
- NVIDIA GB200DGX Superpod - <https://www.nvidia.com/en-us/data-center/gb200-nv172/>

Codes & Standards

- ASHRAE TC 9.9
- Parsloe and M. Ronceray, “BG-29: Pre-Commission Cleaning of Pipework Systems, Amended 6th Edition”, BSRIA, March 2021.
- American Society of Mechanical Engineers, Codes and Standards, “B31.3 Process Piping - 2024
- American Society for Testing of Materials (ASTM), “Standard D1193-99e1 Standard Specification for Reagent Water,” August 2017 (D1193 Standard Specification for Reagent Water)

7. License

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Appendix A. Reliability & Risk Considerations in TCS Pipe Systems

Addition of liquid to rack pipe systems inside the IT space adds components of risk and the need to evaluate that risk and take appropriate measures to reduce the risk severity and probability to a level that is acceptable, within the restraints of optimizing cost and operations.

Risk assessment: There is a need to consider that unforeseen events may impact the project outcomes. Risk assessment is a systematic approach to evaluate threats, comprising risk identification, analysis, and evaluation. There are different approaches on how to assess risk, so it is up to each organization to decide the scope and depth of the analysis. Figure A-1 shows a framework for data center risk assessment, which is an iterative process through the data center lifecycle. The first step is to identify potential threats and assign weights according to relevance. Next is the risk analysis, to quantify the risk level, considering the likelihood and impact of events. Then, the risk evaluation assesses the estimated risk compared to an acceptable level.



Figure A-1: Data center risk assessment framework (source: DCMETRIX)

FMEA for TCS Reliability Analysis

Data center designers are expected to perform Failure Mode and Effects Analysis (FMEA) to reduce the severity and probability of failures while increasing their detectability—ultimately lowering overall risk.

FMEA Process: FMEA begins by identifying potential failure modes, then assigning risk factors:

- **Severity (S)**
- **Probability (P)**
- **Detection (D)**

These are combined into a **Risk Priority Number (RPN = S × P × D)**. Actions can then be taken to reduce RPN by targeting one or more risk factors:

- **Severity** – Modify design to minimize impact of failure modes.
- **Probability** – Use components with proven reliability and installation methods that can be verified.
- **Detection** – Incorporate monitoring technologies (e.g., leak detection, visual indicators).
- **Procedures** – Reduce human error through well-defined MOPs, SOPs, and EOPs.

Given that TCS systems distribute liquid near IT equipment, FMEA is essential for risk mitigation. This need is also emphasized in the OCP ACF white paper on Reference Designs and Best Practices.



Figure A-2: Failure Mode Effect & Analysis

Severity: There are many factors to consider in relation to severity. For example:

- Location of pipe system (above, below, near ITE)
- Value of ITE
- Business value of ITE

Probability: The TCS presents three potential categories of water risk: Pipe failure, connection failure, and condensation. The probability of pipe rupture is generally minimal with proper design, commissioning and maintenance. The risk of condensation should be eliminated by proper design and operation above dew-point. Selection of connection method and level of protection associated with pipe connections is a key discussion. Characteristics of connection

types (thread, flange, grooved coupling, weld, crimped, fused) and installation verification capabilities are discussed in OCP ACF Pipe Connection Guidance WP.

Use of data-based reliability analysis (MTBF) Data based reliability such as “mean time between failure” (MTBF) is a preferred method of evaluating risk. However, MTBF is difficult with pipe connection methods because MTBF requires verification of proper installation for evaluation. As discussed in the **OCP WP Guidelines for Connection of Liquid Cooled ITE**, most pipe connection methods lack a simple inspection process that verifies proper installation. Without verification of proper installation, MTBF has little meaning.

Summary of inspection methods available for different types of connection methods is provided in table A1 from the OCP WP on Connection Methods.

Large data centers will require tens of thousands of mechanical connections, requiring leak proof connection for 20+ years. For example, to ensure reliability of a data center using 20,000 connectors, an MTBF of over 4.4 billion hours is needed to reduce the need for extensive use of leak detection, collection and protection.

Connection Type	Inspection Method to Prevent		MTBF Data
	Leakage	Failure	
ReConnection Methods			
Threaded	None	Visual	N/A
Flange	Torque check?	Torque check	N/A
Grooved Coupling*	Visual	Visual	>5 Billion hours
Fixed Connection Methods			
Weld	X-Ray	X-Ray	N/A
Crimped/pressed	???	???	N/A
Fused	???	???	N/A
Yellow = Leak Protection Recommended. Data from OCP WP Connection Methods 2022			
Table A1: Inspection Methods of Pipe Connections			

Grooved coupling technologies can be designed to support visual inspection as a means of verification of proper installation to avoid leakage and failure. As such, MTBF is a valid measure of reliability with grooved couplings, and it is recommended that MTBF > 4.4 billion hours be demonstrated or that suitable risk prevention measures be included.

Table A2 provides an example of an MTBF analysis of a mechanical coupling method where performance of 18 data center projects over a period of 13 years was performed, providing a sample base of over 150,000 couplings used in data center cooling with no leakage. As no

failures occurred in the study, the actual MTBF of this method is undetermined, but well in excess of 8 billion hours. (One issue occurred with a coupling that was not verified properly installed and correspondingly not included in the study). **Verification of proper installation is required for MTBF analysis.**

Over 8.5 Billion Hours MTBF – With No "F"				
Visual Inspection = No Failures				
Data Center	Location	Year	# of Couplings	Coupling Hours
[Colo Provider]	Cork	2011	1,750	218,274,000
[Colo Provider]	Frankfurt	2012	3,886	450,558,384
Telefonica	Madrid	2012	25,000	2,898,000,000
Green Mountain	Rennesoy	2013	7,000	750,288,000
Telecity / Digital	Amsterdam	2016	2,712	219,346,560
[Colo Provider]	Quincy, WA	2019	1,834	100,136,400
Global Switch	Hong Kong	2019	19,000	1,037,400,000
[Colo Provider]	Dublin	2020	3,100	142,029,600
[Colo Provider]	Marseilles	2020	20,000	916,320,000
[Colo Provider]	Africa	2020	9,700	444,415,200
[Cloud Provider]	Quincy, WA	2021	1,301	48,178,632
[Colo Provider]	Malaysia	2022	26,195	741,213,720
[Colo Provider]	Dublin	2023	3,200	62,515,200
[Colo Provider]	Los Angeles, CA	2023	1,201	23,462,736
[Colo Provider]	Quincy, WA	2023	1,550	30,280,800
[Colo Provider]	Phoenix, AZ	2023	3,891	76,014,576
[Colo Provider]	Hillsboro, OR	2023	5,638	110,143,968
[Colo Provider]	Malaysia	2023	13,130	256,507,680
As of Date:	# of couplings evaluated		150,088	
	hours of coupling service evaluated		8,525,085,456	
8/28/2025	# of issues with proper installation		0	
	# of issues with improper installation/not inspected		1	

Table A2: Example of Connection Method Reliability Study
 Data provided by Victaulic

Auditable Verification of Proper Installation: Improper installation of connections is the leading cause of failure. Traceability of installation significantly reduces risk of improper installation, and likewise the risk of leakage or failure. Identification of the installing contractor on each connection in areas of high risk is used in many industries to provide auditable traceability of proper installation. Welders, for example, are often required to stamp or “sign” each weld in a mission critical project. For critical installations, identification of the installing contractor and/or inspector is recommended for all connection methods in a mission critical space, including flanges, fused connections, grooved couplings, etc.

Detectability: Maximizing detectability is another method to reduce risk. Use of drip trays combined with leak detection is a common method that should be considered with due diligence. With proper pipe design, inspection and commissioning, the probability of significant leakage is exceptionally low, with minimal need for drain lines if leak detection is placed inside the tray. Recommended location of drip trays will vary with perception of risk. Typically, drip trays are used underneath connections that cannot be verified “leak-proof”, and in locations where dripping would have high risk or possibly go undetected (i.e. underfloor).

Use of drip trays - Detection vs Collection: Using drip trays as a means of improving detection of leakage is simple and relatively low cost. Use of drip trays as a means of collecting and draining leakage can be very complex and costly (including drain lines, drain systems, and wastewater treatment). Guidance from a licensed engineer familiar with codes and standards is highly recommended.

Procedures: Human error is often cited as the most common cause of failures. Creation and adherence to procedures is fundamental to operation of mission critical facilities. Creation of SOPs for common operations (e.g., swapping out servers) and MOPs for maintenance items (e.g. IT refresh and swapping out IT racks) as well as EOPs for emergencies (e.g. pump failure) is most important.

Appendix B. Calculations & Selector Tools for TCS Planning

There are a variety of variables to consider in planning loop size. Selector tools can simplify and accelerate the planning process. Validation by a licensed engineer is always recommended. Typical TCS flow vs KW requirement is sometimes approximated as “1.5 LPM/KW”, but this is just a thumb rule and varies with specific heat (i.e. water vs PG25) and ΔT .

The heat transfer formula for fluid flow is $Q = m * C_p * \Delta T$, where:

Q: Heat energy in KW

m: Mass flow rate of the substance in kilograms or pounds per minute

C_p : Specific heat of the substance in J/kg°C or Btu/pound/°F

ΔT : Temperature difference between entering and leaving fluid in °F or °C

[The Engineering Toolbox - Calculating Cooling Loads](#)

By loading basic calculations and data tables into a spreadsheet, rapid evaluation of pipe types, sizes, fluid types and flow conditions can be compared with performance window outputs around KW per loop, per rack, and number of racks per loop.

Example: Estimating CDU capacity, racks per loop, branch line capacity -

Example: [TCS Velocity & Pipe Sizing Tool](#)

For example, CDU performance varies with temperature differential (ΔT), of both the facility water and the IT cooling. Currently, most IT equipment is designed for a $\Delta T = 10^\circ\text{C}$. However, some designs are considering $\Delta T = 20^\circ\text{C}$.

As shown in Fig. B-2, using the pipe sizing tool it can be quickly shown that a CDU using the same pipe configuration delivers 2422 kW at $\Delta T = 10^{\circ}\text{C}$ and 4845 kW at $\Delta T = 20^{\circ}\text{C}$.

Figure B-2: CDU Capacity vs Delta T

PIPE SCHEDULE	HEAT TRANSFER FLUID	VELOCITY (FT/S)	HEADER PIPE SIZE (IN)	BRANCH PIPE SIZE (IN)
Stainless Steel Schedule 10	Propylene Glycol 25%	9.7 3.0 m/s	6 DN 150	2 DN 50
SPECIFIC HEAT (BTU/LBM °F): 0.926		DENSITY (LBM/US GAL): 8.610		

HEADER (ROW)	PIPE SIZE (IN)	PIPE O.D. (IN)	PIPE WALL THICKNESS (IN)	PIPE I.D. (IN)	CROSS-SEC AREA (SQ. IN)	FLOW RATE AT 9.7 (FT/S)		
						GPM	LPM	LPS
	6	6.625	0.134	6.357	31.739	960	3633	60.6

ΔT	MAX ROW KW AT 6 (IN)	MAX RACK KW AT 2 (IN)	KW PER RACK	KW PER RACK	KW PER RACK	KW PER RACK	KW PER RACK	
			50	100	150	200	250	
(°F)	(°C)	(KW)	(KW)	MAXIMUM NUMBER OF RACKS				
18	10.0	2422	278	48	24	16	12	9
36	20.0	4845	555	96	48	32	24	19

Appendix C: 25µm Filtration in TCS – Insights from OVHcloud

[Note - in the 2024 publication of this paper, a lengthy discussion was contributed by OVH Cloud highlighting lessons learned over 15 years of deploying liquid cooled IT. Much of that guidance is now integrated with other inputs in the 2025 version of this paper]

Highlights of the original discussion are provided below:

- OVHcloud successfully deployed 25µm filtration to enhance coolant cleanliness in Technology Cooling Systems (TCS).
- The finer filtration protects components from fouling and supports long-term system performance.
- Makeup water should be filtered to 1µm where possible, to reduce long-term contamination risks.

Filter Placement Strategies

1. Cooling Module (CDU) Level

- **Parallel Filter Configuration**
 - **Pros:** Low pressure drop; energy efficient; compact; good for high-flow, low ΔT (e.g., 5°C) systems.
 - **Cons:** Lower filtration efficiency; partial bypass means slower cleaning.
- **Series Filter Configuration**
 - **Pros:** Full-flow filtration; higher cleanliness; ideal for low-flow, high ΔT (e.g., 20°C) systems.
 - **Cons:** Higher pressure drop; bulkier; increased pump energy; higher CAPEX.
- Air & Dirt Separator technologies should also be considered as part of the CDU itself or the final CDU/TCS configuration.

2. Rack-Level Filtration

- **Pros:** Compact; can be integrated per rack.
- **Cons:** Costly; high component count; higher maintenance; lower overall filtration effectiveness.
- Lesson Learned: OVHcloud abandoned this approach due to high cost and complexity.

Instrumentation & Maintenance Enhancements

- Use differential pressure sensors across each filter to monitor fouling and enable predictive maintenance.
- Incorporate bypass loops for operational flexibility and minimal downtime during filter changes.
- Determine where water chemistry monitoring sensors, controllers, and integration with alarms management systems will be needed. Each customer may have different water quality and water chemistry management SLA's which will drive how the design team integrates these requirements into the contract documents. If this is not clear, ask early to ensure that aftermarket installations do not compromise the process of flushing, cleaning, treating, and conditioning the TCS system.

Key Lessons Learned

- Match filter configuration to flow and thermal design:
 - Use parallel for high-flow, low ΔT .
 - Use series for low-flow, high ΔT systems.
- 25 μ m is a practical balance between filtration precision and system efficiency.
- Rack-level filtration adds complexity and cost—use sparingly or avoid if possible.
- Instrumentation is essential for monitoring, reliability and maintenance planning. This includes how each party responsible for their work in an SLA utilizes this data to support day to day operations, maintenance planning, efficiency management, alarms prioritization, and emergency response.

Appendix D: Flow Control Considerations

To effectively discuss control, it is essential to first understand the system being managed. The system spans from the Coolant Distribution Unit (CDU) to the IT rack, encompassing the piping and connections. While the system was initially designed to support a fixed number of racks, this is not always the case. The number of racks can vary depending on the deployment strategy and the power density of each rack. Consequently, the control system must be adaptable to ensure sufficient liquid flow is delivered to each rack under varying conditions.

Flow Rate and Pressure Drop Considerations

A critical starting point is determining the flow rate required for effective cooling of each rack. Additionally, it is necessary to account for the associated pressure drop, which includes losses through the supply and return piping, as well as the connections, valves, and hoses integrated into the system.

By understanding the total pressure drop and estimating the pressure loss within the supply and return pipes, the CDU's pump speed can be regulated to deliver the required flow rate to each rack at the desired pressure. This target pressure drop serves as the setpoint for the entire system.

Adapting to Changes in Rack Configuration

As racks are added or removed, the pump dynamically adjusts its speed to maintain the set pressure drop, thereby delivering the appropriate flow rate to meet the cooling demands of the connected racks. To ensure equipment reliability and ability to sustain staged connections over time, please review the original contract documents, construction documents, submittals, as-builts, O&M Manuals, and commissioning reports to understand the full capacity and flexibility of the system.

Ensuring Balanced Flow

To prevent unbalanced pressures that may cause some valves to exceed their gauge limits at high flow rates, it is critical to regulate the flow to each rack. This is achieved using flow control valves installed on each branch.

Flow Control Valve Options

There are several types of flow control valves available, each with distinct capabilities:

- **Manual Valves:** Require operator adjustment to maintain desired flow rates.
- **Automatic Valves:** Self-regulating to maintain flow based on system pressure.
- **Control Valves:** Actively adjust flow and pressure based on system feedback.
- **Telemetry-Enabled (Smart) Valves:** Provide real-time flow and pressure data for monitoring.

Selecting the appropriate valve type depends on the specific requirements of the deployment and the desired level of automation and system integration. The pros and cons of control methodologies (manual, automatic & use of telemetry) is a complex discussion beyond the scope of this paper. A summary table comparison is provided in Table D1. As the cold-plate technologies evolve, the benefits of control methodology also evolve and may be suitable for future workstream discussions.

Feature	Manual Balancing Valve	Automatic Flow Limiting valve	Automatic Balancing Valve (Adjustable flow cartridge)	Pressure Independent Control Valve (PICV)	PICV + Smart Control
Control Method	Manual	Calibrated Flow Cartridge, Pressure-independent		Automatic, pressure-independent	Automatic with sensor based optimization
Dynamic Adjustment	No	No		Yes	Yes
Energy Efficiency	Low	Moderate		High	Very High
Monitoring Capability	None	None		Limited	Advanced (flow, temperature, energy)
Cost	Very Low	Low		Moderate	High
Applications	Constant flow/constant pressure systems	Constant flow systems		Variable flow systems	Smart & high-performance systems
Flushable?	Required, method to be evaluated on each valve				

Table D-1 Flow Control Valve Comparison

Wetted Fluid Network Material Compatibility

The selection of materials and connections for Technology Cooling Systems (TCS) must balance performance, compatibility with the working fluid, and long-term reliability. The following guidance outlines key considerations for materials, treatments, and joining methods in wetted fluid networks supporting liquid-cooled IT. Refer to the **OCP Coldplate Liquid Cooling Guidance** for further insight into brass and wetted material selection in direct-to-chip applications.

Stainless Steel – Grades 304 and 316

Both 304 and 316 stainless steel are widely used for TCS applications due to their corrosion resistance and mechanical durability. Adherence to fluid chemistry controls specified in OCP Coldplate guidance requires maintenance of chloride content below 25 ppm, which supports use of 304 stainless to provide cost and supply advantages.

Brass Components

Brass is used selectively within TCS designs, primarily for small components like valves and fittings.

- **Zinc Content:** Brass alloys with zinc content **below 15%** are preferred. Higher zinc content increases the risk of **dezincification**, which can compromise mechanical integrity and release zinc-rich corrosion products.
- If higher-zinc brass is used, it should be verified as **dezincification-resistant** per **ISO 6509 testing**. Examples: UNS C87850, UNS C95500, AMETAL Hot Stamped, Rod or Diecast
- **Plated Brass:** When using plated brass (e.g., nickel-plated), additional care should be taken to ensure the plating layer does not delaminate or corrode under thermal cycling. Compatibility with fluid chemistry and thermal expansion coefficients should be verified.

Improper disclosure of material used in the TCS could result in damage, corrosion, and particulate creation placing the cold plate, CDU, and balance of the TCS at great risk. Ongoing operations that result in ITE changes that introduce new manufacturers of ITE are also

responsible for reporting what materials are used in those systems to ensure water treatment/chemistry programs can take that into account and adjust treatment/dosing parameters.

Appendix E: Considerations for TCS Module Size & Valving

The selection of the TCS module size and use of isolation valves involves several critical factors, including adaptability, circularity, ease of transport and installation, and concurrent maintainability. Let's break down these considerations for clarity:

1. Adaptability & Circularity:

Adaptability for change in KW/Rack - Most TCS loops have predefined limits in terms of total KW capacity. As rack densities increase, the number of rack stations per loop decreases.

Circularity - With modular design planning, which includes addressing concerns about thermal movement, it becomes feasible to remove and reuse TCS modules, a concept known as "circularity." This approach offers significant benefits in reducing the carbon footprint of data center operations.

Module Planning: Advanced planning of module sizing and the location of isolation valves are crucial considerations. For instance, consider the placement of isolation valves within headers:

- **Module Removal:** The addition of a valve between each module enables the isolation and removal of individual modules. Using dual valves between each module enables the maintenance of the valves and reduces the risks of relying on a single valve for module maintenance.
- **Valve Replacement:** Removal of valves for maintenance is simplified with multiple isolation valves.
- **"Blast Radius":** Sizing modules and isolation valve deployment based on isolation of damage in event of failure. Some customers may seek single module isolation capability, with automated actuators to enable automated isolation in emergencies. Other customers may allow for isolation response by header (allowing larger "blast radius" can significantly reduce cost and maintenance).

2. Concurrent Maintainability & Risk Management:

- Apart from valve maintenance, the isolation valve strategy can align with concurrent maintainability and risk management (“blast radius”) strategies. [See OCP/TUI workstream on Concurrent Maintainability]
- Concurrent Maintainability refers to the ability to support standard maintenance activities without disrupting ongoing operations.
- The ability to isolate and remove IT racks or IT rack sections without impacting other IT racks is essential to this discussion. However, this involves a trade-off between cost and complexity.
- It is important to understand the design of your system and these types of features to drive the subsequent development of your operating SLA’s expectations to alarms, leaks, and other operating concerns that require specific response times.

There are two conceptual approaches in use of isolation valves with TCS modules: Isolation valves at end of each rack station module and isolation valves at the ends of the headers:

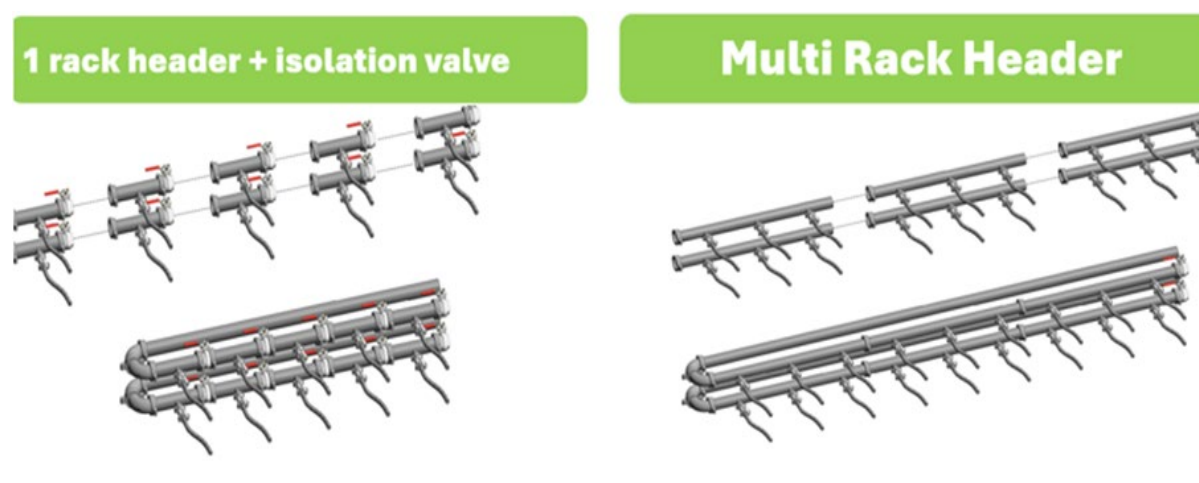


Figure E-1: Modular Approaches to Maintainability & "Blast Radius"

- **Isolation valves at end of each module:**
 - ***Enables Removal and Replacement:*** This setup allows the removal of individual header/branch line modules or replacement to support different IT form factors or branch line requirements.
 - ***Reduced Maintenance Impact:*** Maintenance of the header is reduced to 1-2 modules instead of the entire header. Additional valves add cost and weight.
- **Isolation valves at the ends of the headers:**
 - ***Lower Cost:*** More cost effective from construction perspective
 - ***Blast Radius Impact:*** Shutdown of the entire header during maintenance.

It is essential to consider factors like IT refresh, rack maintenance, concurrent maintainability and header connection maintenance when designing the isolation valve system.

Appendix F: Structural Considerations for TCS Modules

- **Overhead Pipe Distribution Structural Considerations & Design Options:**
- **Underfloor Pipe Distribution Considerations:**
- **Skid Based Distribution Considerations**

Overhead Pipe Distribution Structural Considerations & Design Options:

When installing pipe systems above data center racks, there are several key structural considerations to ensure the safety and functionality of the installation. These considerations include:

- **Facility Rating:** Check the data center's facility rating; that is, the extent to which it is required to continue to operate after a seismic event. Referred to as Occupancy Category (ASCE 7-05) or similar terms (depending on jurisdiction), most data centers need to continue to operate and are Occupancy Category IV. The Occupancy Category determines the Importance Factor for individual items of plant and equipment
- **Load-Bearing Capacity:** Ensure that the data center's structural framework can support the additional weight of the pipe system and any equipment or materials it carries.
 - Pounds per linear foot of pipe system
 - Pounds per square for (PSF) of Ceiling System (& facility)
 - Maximum Point Load
 - Maximum floor loading

Pipe Size		Stainless Sched 10 Pipe + Fluid Wt/Foot			Butterfly Valve Weight Estimates (Lbs)					
NPS (In)	DN (mm)	Cross-sectional Area (sq. in)	Dry Pipe Weight Per Foot (lb/ft)	Pipe & Fluid Weight Per Foot (lb/ft)	Flanged Valve LBS	Flange LBS	Flanged BFV + 2 flanges	Grooved BFV LBS	Coupling LBS	Grooved BFV + 2 couplings
3"	80	8.3	4.4	8.2	13	9	31	6	3.3	13
4"	100	14.3	5.7	12.1	26	13	52	9.3	5.8	21
6"	150	31.7	9.5	23.7	31	19	69	20	9.1	38
8"	200	54.5	13.7	38.1	69	30	129	34	16.6	67
Note: Approximate weights, actual values vary by manufacture, product										
Source: Manufacturer data + ASME B16.5 Forged Flanges Weight Chart, Class 150										

Table F-1: Pipe Weight + Valve Weight Estimation, Stainless Steel + PG25

- Rack, Cable and Equipment Clearance:** Maintain adequate clearance between the pipe system and data center racks, as well as any equipment mounted on the racks, to prevent interference or damage. Consider the height of the pipe system to ensure that it doesn't obstruct access to racks, maintenance areas, or fire suppression systems.

Accessibility for maintenance and inspection is crucial. Plan for cable trays or conduits to run alongside or within the pipe system to manage data and power cables efficiently. Proper cable management helps maintain a tidy and organized data center.

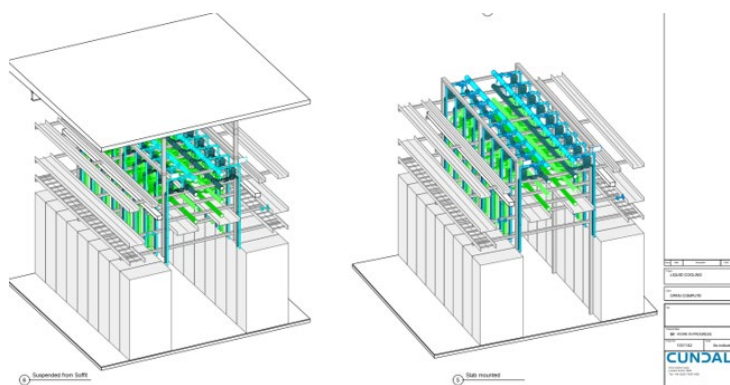


Figure F-1 TCS Structural Considerations - Loading & Clearance

- Attachment Points and Movement Considerations:** Securely anchor the pipe system to the building's structure, ensuring it can withstand potential seismic activity, vibrations, or other external forces. Implement movement and anti-vibration measures, such as shock absorbers or isolation mounts, if necessary, to reduce vibrations and their impact on sensitive equipment.
- Leak Detection and Prevention:** (See Appendix A for Risk & Reliability discussions) Location of piping and integration of drip trays and leak detection requires significant evaluation.
- Future Expansion:** Consider the potential for future expansion of the data center or changes in technology that may require modifications to the pipe system. Design with flexibility in mind.

Underfloor Pipe Distribution Options:

Underfloor liquid distribution to IT racks involves significant considerations to ensure the system's effectiveness, reliability, and safety. Key considerations for this process include:

Leak Detection and Prevention:

- Implement robust leak detection systems to quickly identify and respond to any leaks. Consider secondary containment measures to prevent liquid from reaching critical equipment. Key concern in overhead pipe systems.

Maintenance and Accessibility:

- Design the system with maintenance in mind, ensuring easy access to components for inspections, filling, draining, expedited air removal, repairs, chemical treatment, and replacements. Implement regular maintenance procedures to keep the system in optimal condition.

Compatibility with Other Infrastructure:

- Ensure that the underfloor liquid distribution system does not interfere with other critical infrastructure components, such as power distribution, cabling, FWS piping, stanchions, fire suppression systems, etc.

Planning for Future Growth:

- Consider scalability when designing the liquid distribution system, allowing for easy expansion as the data center grows or as cooling requirements change.

Training:

- Provide training for data center personnel and any other organizations with SLA/contractual responsibility for the operation, maintenance, and safety procedures associated with the liquid cooling system.

Compliance and Regulations:

- Ensure that the installation complies with relevant codes, standards, and regulations governing data center cooling systems and safety.

Skid Based Distribution Methods: Skid-Based Distribution Methods: Prefabricated modular pipework can be integrated into skids that provide structural support and anchor points for expansion control. These frames can also support lighting, sprinkler piping, cable trays, fiber, and bus bars.

For higher temperature classes (e.g., W40, W45, W+), thermal insulation may be needed to reduce heat loss into the technical space. Prefabricated skids allow pipework to be delivered pre-insulated, with optional leak detection tape beneath the insulation if required.

Appendix G: Commissioning for Cleanliness Considerations –

As previously outlined, Technology Cooling System (TCS) piping networks must meet rigorous standards for water quality, particulate filtration, air removal, and fluid chemistry. These systems support a variety of liquid-cooled IT solutions, including Door Heat Exchangers, Immersion Cooling, and Cold Plate systems.

Among these, **Cold Plate systems**—particularly those incorporating **micro-channel heat exchangers**—have the most demanding requirements for fluid cleanliness and chemical stability. The recommendations in this appendix are tailored to meet those requirements and ensure system reliability and performance.

Objective of Appendix G: Provides guidance in the following critical areas:

- **Prep & Cleaning procedures** for prefabricated pipe modules and assemblies
- **Commissioning processes** to onboard and test system with operating fluid (PG25)
- **Instrumentation & Controls** available as part of the design to support the measurement and verification of operating parameters.
- **Portable (Temporary) Instrumentation, Tools & Equipment** needed to supplement the designed configuration of the system to achieve measurement and verification of intended performance, water quality, and reliability.
- **Ongoing cleanliness standards** to maintain fluid integrity during the onboarding of IT equipment (ITE) and auxiliary subsystems

Preparation Prior to Shipment – Prefab Header Modules & Branch Lines

Prefabricated TCS Header Module Checklist

Section	Checklist Item	Reference
1. Pre-Cleaning Assumptions - Header Modules	304 or 316 stainless steel	Basis of procedure
	Confirm proper welding meeting requirements of ASME B31.3 and following guidance of AWS D10.18	ASME B31.3, AWS D10.18
	Pressure tested to 1 –1.5× the design working pressure	ASME B31.3 – Process Piping
	Modules passivated prior to delivery	ASTM A380/A380M-25
	All TCS modules and assemblies cleaned to ASTM A380. Modules and assemblies should be kept sealed until immediately prior to installation.	ASTM A380/A380M-25
	Jobsite passivation required if welding during install	ASTM A380/A380M-25

Table G-1: Pre-Commissioning Checklist, TCS Pipe System Modules

(**Note** - Commissioning guidance provided in this section is primarily focused on stainless steel pipe systems. However, it may also apply to other pipe materials, including non-metals)

Technology Cooling System (TCS) header modules intended for prefabrication and off-site assembly should be cleaned, passivated, pressure testing, and sealing prior to shipment. These procedures align with best practices drawn from:

- ASME B31.3 - Process Piping or ASME B31.9 - HVAC Systems
- AWS D10.18 – Guide for Welding Austenitic Stainless-Steel Pipe
- ASTM A380 / A967 – Standard Practices for Cleaning and Passivation of Stainless Steel

Prior to shipment, modules should be:

- **Cleaned** to remove oils, fabrication residues, and particulates from internal surfaces. (note – Objective is a preliminary cleaning. Modules will be cleaned and flushed to operational standards as part of final assembly)
- **Passivated** to restore the protective chromium oxide layer after welding or hot work
- **Pressure tested** to 1.3–1.5× the design working pressure
- **Drained, dried, and sealed** with a dry nitrogen purge or equivalent inert gas to prevent contamination and corrosion during transit. It is recommended that modules be sealed with tamper-evident protective caps, to remain in place until immediately prior to installation.

Passivation Considerations - Passivation is required after welding, hot work, or corrosion but may be addressed in the module fabrication process. The process involves applying an acid solution, typically nitric acid or citric acid, to remove contaminants like free iron and scale that can cause rust or localized corrosion. Passivation allows the natural chromium oxide layer on stainless steel to form or regenerate, which provides protection against oxidation.

Jobsite Passivation: If welding or hot work is performed on-site, passivation should follow the cleaning phase per mechanical specs (e.g., ASTM A380/A967). ASTM A967 recommends 4–10% citric acid (preferred over nitric acid), typically applied for ~20 minutes at 70–120°F. A thorough post-passivation flush is essential to remove all acid and residues, preventing recontamination of the TCS, CDU, and cold plates. Residual chemicals or particulates can cause damage over time, making effective flushing a critical step.

Prefabricated TCS Branch Lines (Rack Piping) Checklist

Section	Checklist Item	Reference
1. Pre-Cleaning Assumptions - Rack Piping (AKA Branch Lines)	304 or 316 stainless steel or materials meeting wetted material guidance referenced in Appendix E and OCP ColdPlate Liquid Cooling Guidance	OCP Modular TCS Appendix E, OCP Cold plate Liquid Cooling Guidance
	Rack Piping should be pre-assembled, cleaned and pressure tested and delivered as a sealed unit.	
	Use of threaded connections on jobsite should be avoided when possible. Standardization on BSPP is recommended	OCP WP <i>Guidelines For Connection Of Liquid Cooled Ite To Data Center Facility Systems</i>
	Use of pipe tape and pipe dope should be avoided to reduce risk of fluid contamination	OCP Cold plate Liquid Cooling Guidance
	Pressure tested to 1–1.5× the design working pressure	
	Rack Piping Assemblies should be cleaned to ASTM A380. Assemblies should be kept sealed until immediately prior to installation.	ASTM A380/A380M-25

Table G-2: Pre-Commissioning Checklist, TCS Branch Lines (Rack Piping)

The smaller size of the branch lines and inclusion of flow control valves necessitates a separate flushing procedure than the header pipe, to be performed after the header pipe is fully flushed and cleaned. Branch line assemblies should be delivered cleaned, pressure tested and sealed up to the point of installation

- **Off-site Assembly and Testing:** Valve trains should be pre-assembled, cleaned, and pressure-tested and sealed off-site whenever possible. This improves quality control and reduces on-site contamination risk.

- Avoid Use of Threaded Connections** - As noted in the OCP WP *“Guidelines for Connection of Liquid-Cooled ITE to Data Center Facility Systems,”* threaded connections cannot be reliably verified for leak-free installation. TCS cleanliness requirements further limit the use of pipe tape and thread sealants. If required, threaded joints should be assembled and tested in a controlled environment. BSPP is the recommended thread type.

Hydrostatic Test, Cleaning, Flushing, Purging of Installed TCS Pipe System.

This guidance is based largely on input from two key Open Compute Project (OCP) white papers:

- Coldplate Workstream on PG25** *“Guidelines For Using Propylene Glycol-Based Heat Transfer Fluids In Single-Phase Cold Plate-Based Liquid Cooled Racks”* –
- Guidelines for Pre-commissioning TCS Manifolds** (March 2025) *“Guidelines for Pre-Commission Preparation of Technology Cooling System (TCS) Row Manifolds in Liquid-Cooled Data Centers”*

Section	Checklist Item	Reference
Hydrostatic Test	Ensure all stakeholders agree on procedures and materials	Guidelines For Pre-Commission Preparation Of TCS Row Manifolds
	Define and document P&ID for hydrotesting and flushing	
	Clean hydrotest equipment prior to use	
	Gradually fill and vent system	
	Hydrotest at 1.3 -1.5x working pressure per ASME B31.3 or ASME B31.9	
	Avoid disassembly post-test unless necessary; retest if disassembled	
	Flush immediately after hydrotest	

Table G3: Hydrostatic Test of TCS Pipe System Checklist

TCS Header Pipe Cleaning –A key decision in preparing the system is whether to use the CDU (Coolant Distribution Unit) or a temporary flushing rig for manifold and header cleaning and flushing.

- **Using the CDU** – If the CDU is capable of providing the required filtration and flow rates, it offers the simplest solution.
- **Using a Flushing Rig** – If the CDU cannot meet filtration and flow requirements, a temporary flushing rig must be used for both cleaning and the initial flushing phases.

Section	Checklist Item	Reference
Preparation & Planning	Confirm electrical power, instrumentation, and spare consumables	Guidelines For Pre-Commission Preparation Of TCS Row Manifolds + additional industry inpute
	Specify equipment needs, including flushing skid configuration	
	Perform risk assessment and safety plan review	
	Verify water sources, chemical compatibility, and disposal approvals	
	Align cleaning/flushing schedule with commissioning timelines	
	Ensure all stakeholders agree on procedures and materials	
Initial Flush	If CDU filtration and flow does not support flushing, a flushing rig can be used for the initial flushes, with CDU being used for final stages.	
	Use loop backs (cross connects) on the header supply & return piping for flushing of header system for intial flushes. Rack valving to remain isolated until header system is cleaned	
	Fill with "Procedure Water" with <50 µS/cm conductivity and <1000 CFU/ml bacteria	
	Bleed air, initiate flush pump, record flow & dP. Flush > 4 hrs maintaining flow rate above limits in BSRIA table	
Cleaning (2nd Flush)	Maintain pH and conductivity; monitor differential pressure across filters	
	Initial recirculation with 50-100 µm filter to remove debris	
	Add chemical cleaner, recirculate at or above minimum velocity recommened by chemical provider and operational velocity for duration recommended (> 4 hrs).	
	Drain system completely using nitrogen (<5 psig) if needed	

Table G4: Cleaning of TCS Pipe System Checklist

Passivation & Flushing – Initial stage to be performed using a temporary flushing rig with supply and return piping cross connected, CDU and branch lines (rack piping) isolated. When header piping is verified within spec for cleanliness, flushing rig can be removed, CDU and branch lines connected circulation of system continued in preparation for layup or in-service deployment of ITE,

Section	Checklist Item	Reference
3rd Flush	Connect CDU, install 25µm filters	Mixture of guidance from <i>Guidelines For Pre-Commission Preparation Of TCS Row Manifolds</i> + Industry input
	Check and calibrate meters (pH, conductivity, bacteria, refractometer)	
	Use loop backs on hot/cold rack drops for flushing. (if load banks are in place, connect rack piping to load banks)	
	Deploy Procedure Water with <50 µS/cm conductivity and <1000 CFU/ml bacteria.	
	Bleed air, initiate flush pump, record flow & dP. Flush > 4 hrs maintaining flow rate above limits in BSRIA table	
	Repeat fill/recirculate/drain until targets met	
	Isolate valves to ensure flushing of all system legs	
	Flush with Procedure Water, recirculate between 8x - 20X system volume	
	Repeat fill, recirculate, drain (or bleed and feed) until outlet conductivity <60 µS/cm or within 10 - 20 µS/cm of inlet. Include blow-down of all "dead legs"	
	Target final conductivity <60 µS/cm, turbidity <5 NTU. Water to meet glycol manufacturer requirements, including silica content	
4th Flush (if going into service)	If system is going directly into service, fill with PG25, bleed air	
	Circulate using CDU with 25 Micron filters	
	Replace all CDU Filters	
Layup - If system is not put in	Circulate biocide-treated water, drain, and dry	
	Seal system with exception of purge inlet and vent	
	Purge with nitrogen from lowest point	
	Monitor oxygen content at vent (<1%)	

Table G-5: Passivating & Flushing of TCS Pipe System

Ongoing Testing and Maintenance of the TCS Pipe System

Routine Monitoring and Testing- specific parameters and ranges are listed in the **Coldplate Workstream on PG25**. Regular monitoring ensures system stability and longevity:

- pH to prevent corrosion.
- Glycol concentration stability or other fluid specifics if glycol is not used.
- Corrosion indicators (copper, iron levels) via periodic fluid analysis.
- Microbiological activity.
- Particulate levels through on-site turbidity testing.
 - Liquid particle size and quantity counters may be required by the owner to support both construction and operations. These instruments may be integrated as part of the CDU, or field installed as part of the overall TCS.
- Ongoing air removal, system operating pressures, and make up water requirements as air continues to work its way out of the system.

Annual Analytical Testing - (Also recommended after extreme thermal, pressure, or seismic event) Conduct external lab analysis in addition to your onsite continuous monitoring and water chemistry management program to assess:

- Inhibitor concentrations.
- Microbiological growth (bacteria monitoring).
- Fluid degradation (oxidation, breakdown products).
- Particle size and count

System Adjustments and Corrective Actions

- Inhibitor boosting if corrosion inhibitors fall out of range.
- pH adjustment if pH is out of range
- Enhanced filtration if particulate levels exceed acceptable limits.
- Biocide additions if microbiological activity is not controlled.
- Full system drain, flush, and refill for severe contamination or fluid breakdown while monitoring space humidity levels and temperature of fluid to prevent condensation during system restoration efforts.

Addition of ITE: Preventing Contamination and Air Introduction When Adding Liquid-Cooled IT Equipment to the Technology Cooling System (TCS)

Integrating liquid-cooled IT equipment into a new or existing Technology Cooling System (TCS) requires careful planning and execution to prevent contamination and air ingress. This is critical to understand during the construction and operations phases that are attempting to manage equipment installation, startup, testing, cleaning, and eventual interconnection to TCS at various stages in their lifecycle.

General Pre-Integration Requirements

- **Coolant Consistency** Use the same fluid throughout the TCS. Even fluids labeled similarly (e.g., PG25) may differ in chemical additives and compatibility. If ITE has arrived charged with nitrogen, air, or other gases, develop procedure to properly vent the gases or air and fill ITE from either:
 - The TCS (requires accumulator and CDU compensation), or
 - A fill cart using the same coolant.
 - Work closely with the contractor and/or owners water chemistry service provider to ensure any other additives such as inhibitors are not diluted and consistent through the now interconnected TCS system, ITE, and CDU.
 - Regardless of whether the TCS is filled as a whole or by component, air will be present in the system. Effective air removal depends on the quality of the air separator, vent, and removal design. If the TCS lacks built-in air removal infrastructure, contractors may use temporary separators, vents, or devices during flushing, cleaning, and commissioning. Similar strategies may be needed during future ITE rack swaps, upgrades, or expansions.
- **Factory Cleaning** Verify the ITE has been factory-flushed and is free from residues, oils, and particulates.

- **Leak Testing** Conduct hydrostatic or pressure testing of the ITE before connection to confirm leak-free integrity.

Checklist Item	Requirement / Action	Notes
Coolant Consistency	Ensure same coolant is used throughout the TCS	Even fluids labeled 'PG25' may vary in additives—confirm compatibility
Coolant Consistency	Fill IT equipment using:	- TCS source (requires accumulator + CDU compensation) - OR fill cart with matching fluid
Factory Cleaning Verification	Confirm IT equipment has been factory-flushed and cleaned	Free from residues, oils, and particulates
Leak Testing	Perform hydrostatic or pressure test on IT equipment	Must confirm leak-free integrity prior to connection

Table G6: Onboarding IT Equipment to TCS Precheck Summary

Connection Method Considerations To Avoid TCS Contamination –

Vent / Drain-Enabled Connection Method - Sampling/venting/flushing at the point of connection provides the highest level of confidence in compatibility and cleanliness, but can incur logistic challenges in an operating data center. Using dual isolation valves with a vent/drain port between them allows controlled flushing, sampling, and air removal at the point of connection.

Steps:

1. **Isolation:** Keep ITE isolated from the TCS during setup.
2. **Fill & Flush:** Fill with clean coolant from TCS or matching fill cart via return-side vent.
3. **Transport ITE to Install site**
4. **Sampling:** Draw fluid from the vent for chemistry validation and cleanliness inspection.
5. **Air, Dirt Removal:** Use vent to purge air and flush surfaces before TCS flow initiation. Consider early design strategies to incorporate more advanced permanent or temporary air removal technologies where possible.
6. **Final Connection:** Shut vent. Slowly open return-side valve to allow flow into TCS.

Advantages:

- Enables fluid sampling at the connection point
- Allows controlled flushing and venting
- Reduces risk of air or contamination entering the TCS
- Ideal for maintenance or branch-line rework as well

Considerations:

- Collection and removal of sample/flush content (<500 ml) at connection site
- If ITE is delivered with PG25 water-glycol mixture installed, it is important to verify that the fluid is the same manufacturer, concentration of glycol, and chemistry in the TCS. Once introduced into the ITE some dilution may occur requiring re-testing and incorporating additional chemicals to return the system back to acceptable operating parameters.

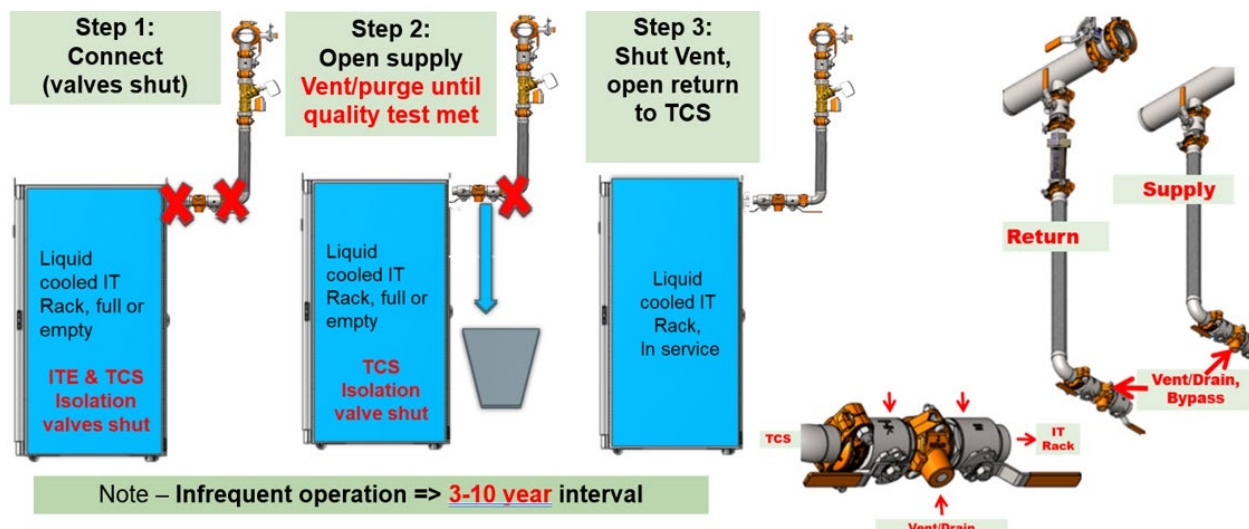


Figure G-1 ITE Rack Connection Considerations - Double ball valve with Vent Drain

Checklist Step	Requirement / Action	Advantages / Notes	Additional Consideration
Isolation	Keep ITE isolated from the TCS during setup	Prevents premature contamination or fluid mixing	Use dual isolation valves with vent/drain port
Fill & Flush	Fill ITE with clean coolant from TCS or matching fill cart via the return-side vent	Ensures initial fluid in ITE matches TCS and is clean	Ensure coolant source is clean and compatible
Transport	Move the ITE to the installation site after filling	Must maintain cleanliness during transport	Maintain sealed conditions during transport
Sampling	Draw fluid from the vent for chemistry validation and cleanliness inspection	Enables compatibility and cleanliness check before connection	Collect sample in clean container for analysis
Air, Dirt Removal	Use vent to purge air and flush surfaces before initiating TCS flow	Removes air and particles to protect TCS	Ensure disposal of purge fluid (<500 ml) at site
Final Connection	Close vent, then slowly open return-side valve to allow flow into the TCS	Allows safe, clean integration of ITE into the system	Monitor flow initiation for anomalies

Table G7 - Adding IT Equipment Using Vent / Drain enabled Connection Method

“Drip-less Connection Without Vent/Drain”

Drip-less connectors simplify connection methods but do not enable sampling, venting or flushing at the connection point. Additional precautions are necessary:

Steps:

1. **Pre-fill ITE:** Fill using clean, filtered coolant, avoiding air entrapment.
2. **Air Mitigation:** Use auxiliary vacuum degassing or air purging tools to remove air from ITE before connection.
3. **Transport To Installation Site -**
4. **Clean Surfaces:** Thoroughly clean both mating surfaces before connection.

5. **Monitor:** After flow is initiated, closely monitor for signs of air or particulate ingress.

Checklist Step	Requirement / Action	Precautions / Notes	Additional Considerations
Pre-fill ITE	Fill ITE using clean, filtered coolant; avoid air entrapment	Use closed-loop system; avoid open-air transfer	Use fine-mesh filtration (<50 µm) during fill
Air Mitigation	Use vacuum degassing or air purging tools before connection	Essential due to lack of venting capability in drip-less connectors	Follow air removal protocols (vacuum-assisted or active venting)
Transport to Installation Site	Transport ITE carefully to preserve cleanliness and seal integrity	Protect against recontamination during transport	Avoid unsealed exposure to environment
Clean Surfaces	Clean both mating surfaces thoroughly before making the connection	Use gloves, caps, and clean handling protocols	Inspect and verify no debris or residue remains
Final Connection Monitoring	After initiating flow, monitor for signs of air or particulate ingress	No sampling possible; monitoring must be adapted to each ITE system	Have protocol for corrective action if issues are detected

Table G-8: Adding IT Equipment to TCS Using "Drip-Less" Connection - no vent / drain at connection point

Considerations:

- Higher risk of trapped air or undetected contamination
- No sampling possible at time of connection. Method for monitoring air, dirt will vary with each ITE system

Contamination and Air Ingress Prevention:

- **Filtered Fill Systems:** Recommend using fine-mesh filtration (<50 µm) when transferring coolant.
- **Closed-Loop Filling:** Avoid open transfer methods; use sealed systems for fill and flush operations.
- **Clean Handling:** Use gloves, caps, and cleanroom protocols when working with open pipe ends.

- **Air Removal Protocols:**

1. Implement vacuum-assisted fill or active venting processes prior to connection.

2. **Coalescing Air and Dirt Separator in Liquid Cooling Systems**

A coalescing separator accelerates air removal through multiple mechanisms

- **Microbubble Coalescence:** Internal media (e.g., wire mesh, fabric, or structured packing) merge microbubbles into larger ones that rise and vent more easily.
- **Low-Velocity Chamber:** A slow-flow zone allows entrained air to come out of solution.

- **Centrifugal Separation:** A tangential inlet promotes cyclone-like separation of air and debris.
- **Enhanced Surface Area and Continuous Venting:** These features reduce purge times from days or weeks to minutes or hours.

If not included in the design, adding a coalescing separator during construction or commissioning can aid in flushing, cleaning, and air removal, and should be considered in 3D coordination and field planning. Temporary deployment is especially valuable when space or budget limits permanent installation.

After commissioning, integrated units continue removing residual microbubbles under varying operating conditions.

Key Benefits:

- **Faster Commissioning:** Rapid air removal improves startup time.
- **Improved Heat Transfer:** Water transfers heat far better than air, ensuring CDUs and cold plates operate at full capacity.
- **Higher Thermal Efficiency:** Properly purged systems prevent thermal derating.
- **Reduced Fan Power & Energy Use:** Better coolant performance reduces reliance on FCS fans and pumps.

Appendix H: Thermal Ride-Through Considerations of the TCS

Thermal ride-through refers to the duration a **Technology Cooling System (TCS)** can maintain IT equipment within safe temperature limits after a power loss or failure of active cooling infrastructure (e.g., pumps, chillers). This metric is critical for evaluating system resiliency, particularly in high-density IT environments.

Key Concepts:

- **Thermal ride-through** leverages the **thermal mass** of coolant and components to temporarily absorb heat, allowing time for system recovery or failover.
- As **IT chip power densities increase**, maintaining operational resiliency becomes more challenging.

ASHRAE TC9.9's Sept 2024 bulletin on cold plate resiliency emphasizes the importance of calculating and maximizing thermal ride-through in liquid-cooled systems.

1. Influencing Factors:

- **Heat Load (Q):** The rate of heat generated by IT hardware (in watts).
- **Thermal Mass (M):** Total mass of coolant and materials that store heat.
- **Specific Heat (C):** Energy required to raise the temperature of system materials.
- **Temperature Margin ($T_{\text{critical}} - T_{\text{initial}}$):** Safety buffer before equipment reaches critical limits.
- **System Design:** Ability to passively dissipate heat when active components fail.

2. Define the Key “Thermal Ride Through” Equation

The thermal ride-through time (t) is governed by the **heat balance equation**, where:

- M = Mass of the thermal components (kg)
- C = Specific heat capacity ($\text{J/kg} \cdot ^\circ\text{C}$)
- $(T_{\text{critical}} - T_{\text{initial}})$ = Temperature margin ($^\circ\text{C}$)
- Q = Heat load (W)

$$t = \frac{M \cdot C \cdot (T_{\text{critical}} - T_{\text{initial}})}{Q}$$

3. Gather System Data

- Measure or estimate the **mass of the coolant** (based on the volume of liquid and its density).
- Identify the **specific heat capacity** of the coolant (e.g., water: ~4,186 J/kg·°C; glycol mixtures may vary).
- Determine the **total heat load** of IT equipment (sum of power draw in watts).

4. Perform the Calculation

- Plug the values into the equation.
- Ensure units are consistent (e.g., convert all temperatures to Celsius, mass to kilograms, and power to watts).

Example Calculation

Assumptions:

- Coolant volume = **100 liters** (0.1 m³)
- Coolant density = **1,000 kg/m³** (for water)
- Specific heat of water = **4,186 J/kg·°C**
- Heat load = **10,000 W (10 kW)**
- Initial coolant temperature = **25°C**
- Critical temperature = **40°C**

Calculation:

1. **Mass of the coolant:** $M = 100 \text{ liters} \times 1,000 \text{ kg/m}^3 = 100 \text{ kg}$

2. **Temperature margin:** $T_{\text{critical}} - T_{\text{initial}} = 40 - 25 = 15 \text{ }^{\circ}\text{C}$

3. **Plug into the formula:** $t = \frac{100 \cdot 4,186 \cdot 15}{10,000} = 62.8 \text{ seconds (approx. 1 minute)}$

4. Adjust for System-Specific Factors

- Include **thermal inertia** of other system components like ITE, CDU if significant.
- Factor in heat dissipation from passive mechanisms, such as radiative or convective cooling.

This result provides an estimate of how long the system can maintain safe operating temperatures after the cooling system is disrupted, based on volume of the pipe system. Other factors, including volume of CDU and tanks attached to the pipe system as well as thermal inertia of the IT system will impact this value.

Appendix I: Service Level Agreement Considerations

A Service Level Agreement (SLA) for a **Technology Cooling System (TCS)** supporting **liquid-cooled IT in a colocation data center** must clearly define responsibilities, performance criteria, and coordination protocols across three key stakeholders: the **colocation provider**, the **design team**, and the **IT tenant**.

The SLA should address the following core elements:

1. **Cleanliness & Maintenance:**

- Establishes standards for flushing, passivation, particle removal (e.g., ASHRAE 25 μm), and ongoing filtration.
- Requires documentation and turnover of procedures, monitoring equipment, and any temporary infrastructure used during construction to support operational readiness.

2. **Flow Control & Hydraulic Balancing:**

- Defines flow rate and pressure drop expectations at IT interfaces.
- Includes use of meters and valves for flow validation and the transfer of hydraulic models to support future planning.

3. **System Integrity & Leak Management:**

- Specifies acceptable piping materials and connections.
- Outlines leak detection methods, containment strategies, and notification protocols.

4. **Reliability & Performance Metrics:**

- Sets targets for MTBF, redundancy (e.g., N+1), maintenance intervals, alarm parameters, and response times.
- Includes efficiency metrics such as PUE.

5. **Commissioning & Documentation:**

- Details flushing, testing, and system validation plans.
- Requires full turnover of documentation, as-built drawings, and witnessed acceptance testing.

6. Interface & Demarcation:

- Clearly identifies physical and data handoffs, telemetry integration, emergency shutdown procedures, and system architecture (e.g., SCADA, PLC, AI).

7. Legal & Insurance Considerations:

- Covers risk transfer, contractual obligations by delivery model (design-bid-build, design-build, IPD), and liability across the system lifecycle.
- Assigns penalties for non-compliance with flow/temperature targets and defines insurance responsibilities for liquid-cooled IT risk exposure.

This SLA framework ensures clarity, accountability, and operational resilience for mission-critical liquid-cooled environments.

SLA Category	Operational Responsibility	
	Colo Provider (Facility Owner)	Tenant (IT Owner)
Cleanliness Standards & Maintenance	Maintain cleanliness of facility-side TCS loop; ensure filtration and flushing to 25 μ standard	Maintain cleanliness beyond demarcation; filter in-rack cooling loops
Flow Control & Hydraulic Balancing	Ensure stable loop flow and pressure at tenant interface; maintain CDUs	Ensure rack components comply with flow/pressure requirements
System Integrity & Leak Risk	Owens leak detection and pipe integrity up to demarcation	Own and maintain rack plumbing and manifolds; detect local leaks
Reliability & Availability	Maintain uptime of facility-side TCS; perform routine maintenance	Design for fault tolerance in IT cooling; respond to maintenance windows
Commissioning & Documentation	Provide documentation and verify commissioning of facility TCS	Witness commissioning at rack interface; review documentation
Interface Definitions & Demarcation	Define facility-to-tenant interface and response procedures	Comply with demarcation and emergency procedures
Legal, Financial, and Insurance	Carry insurance for facility infrastructure; define liability boundaries	Insure IT equipment; accept liability for tenant-side failures

Table I: Service Level Agreement Responsibility Matrix (Conceptual)