Modular Technology Cooling System for "Cloud Scale": Design & Delivery of Liquid To Rack Distribution Systems

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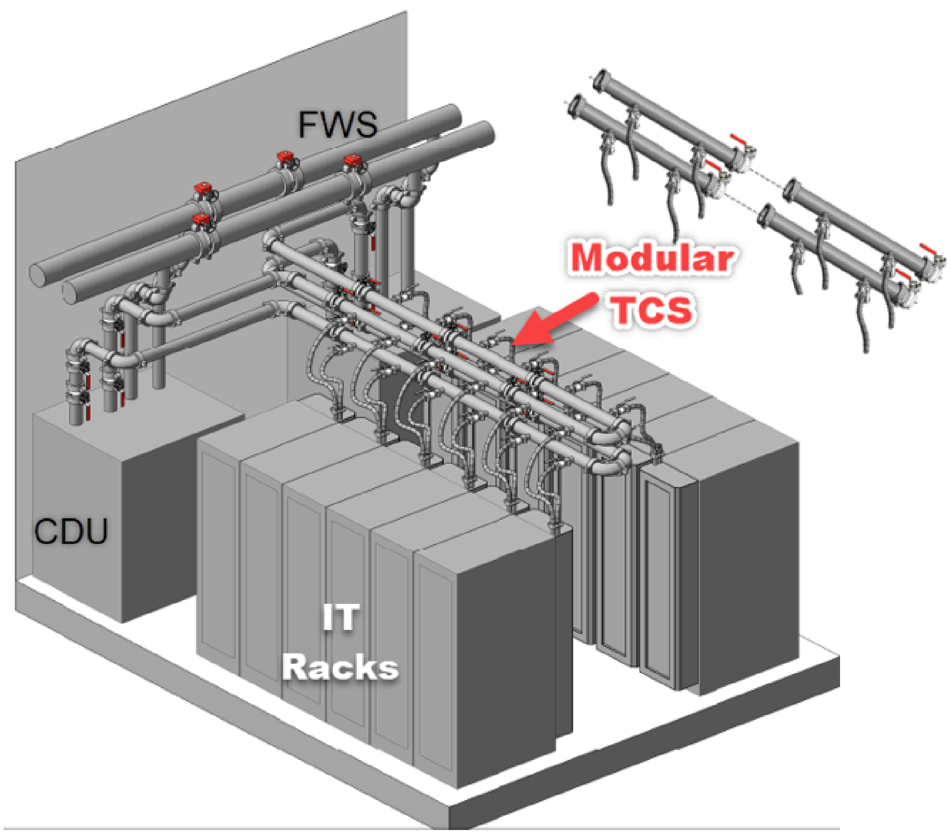
Executive Summary

Liquid cooling technology in IT systems has a longstanding history, primarily in single-purpose applications with defined requirements and limited quantities. Customized liquid distribution systems tailored to specific needs have been the norm.

The data center and IT industries are constantly looking for more efficient, reliable and sustainable cooling systems approaches to satisfy the stringent thermal requirements of the new power-hungry and high-density electronic system. The exponential rise in demand for liquid cooled chips has ushered in an era of cloud scale deployments of liquid distribution in data centers. These projects, growing to deployments of hundreds of megawatts, come with uncertain IT requirements, challenging the conventional design and delivery planning norms. Factors such as rack power densities, "ΔT" (fluid temperature rise), operational temperature ranges, pressure drops, liquid flow, and water quality requirements are expected to evolve over time, posing a significant challenge in this dynamic landscape.

This whitepaper delves into critical design and delivery considerations associated with modular design and delivery of water-based Technology Cooling Systems (TCS) at cloud scale. It addresses the pressing need for advancement in modular design, adaptability, circularity, sustainability, and pipe system performance to support these large-scale deployments effectively. The paper also explores the development of selection tools aimed at simplifying the intricate process of implementing water based TCS solutions.



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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 300MW. 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. 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

Advancing the modularity of the TCS simplifies the design process, use of standardized reference designs and standard parts and assemblies. Modular designs simplify the scalability and adaptability of the TCS to meet changes in ITE and facility requirements.

2.4 Scale

Modularity in design and construction plays a crucial role in achieving large-scale production efficiently. Traditional job site construction is often slower and less accurate. In contrast, producing modular components in a factory setting and then assembling them on-site generally leads to lower costs through economies of scale and improved quality due to better defect control. Offsite manufacturing also enhances schedule reliability, as components can be prepared away from the main construction site without disrupting ongoing work there. Furthermore, modular construction supports rapid, large-scale delivery by utilizing offsite construction techniques, streamlined supply chains, and optimized inventory management. It also helps in minimizing waste and reducing risks associated with construction.

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 @ CloudScale - Design & Delivery Guidance

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 filtration down to 25µm, which is very difficult to achieve with job-site construction. Off-site fabrication of TCS modules enables greater cleanliness and more sustainable practices in manufacturing and delivery of pipe systems.

- **Sustainability:** In addition to the sustainability advantages offered by offsite manufacturing, modular design and delivery advances 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:** The escalation of demand for liquid cooled IT is creating global supply chain challenges. Inventory and regional manufacturing centers of excellence can help address this challenge.

- **Risk/Defect Reduction:** Repetitive manufacturing methods in offsite facilities enable failure reductions and optimize testing and quality control methods.

- **Jobsite Skilled Labor Hours**: Modular solutions reduce the jobsite labor hour requirement.

3.2 Requirements for Modularity in TCS Pipe Systems

- **Constructability**
  - Minimal thermal movement
  - Easy alignment of connection methods
  - Movement accommodation
  - BIM Enabled DfMA

- **Reliability**
  - Visual Inspection Validation
  - Auditability, Traceability
  - Brittle Fracture Prevention
  - Thermal tolerance - 20 °C to 70 °C
  - Concurrently maintainable

3.2.1 Constructability

Minimal Thermal Movement

A key consideration in pipe system design is accounting for thermal expansion and contraction. Pipes are often subjected to temperature variations, which can lead to significant thermal movement. The TCS pipe system design temperature range is significant, from 20 °C to 70 °C. Construction is typically done around 20C. Normal operation (for cold plate and immersion) is 30 °C-50 °C. Peak conditions may be as high as 70 °C.

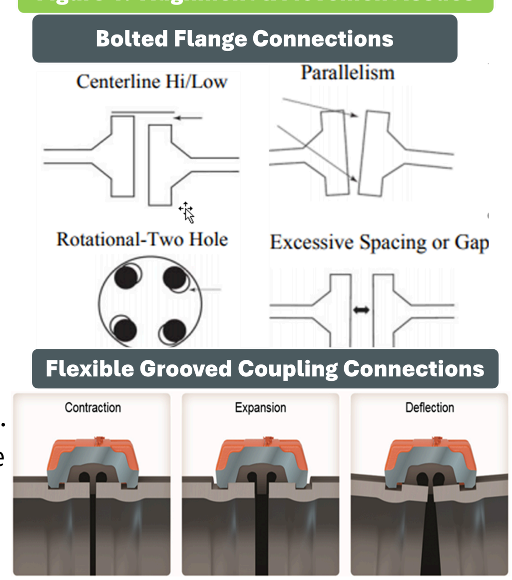
To achieve modularity, engineers must design systems that minimize the amount and impact of movement. Utilizing materials with low coefficients of thermal expansion can help mitigate the effects of temperature fluctuations. Pipe systems are three dimensional, and thermal movement can create stress in all directions, creating problems not only in installation, but also maintenance. Minimization of thermal movement and use of connection methods that can accommodate thermal expansion and contraction can enable system stability, modularity and adaptability over the life of the data center.

Easy Alignment of Connection Methods

Achieving a modular pipe system requires simple integration between pipes and their connecting components in a variety of operational conditions. Prefab construction is complicated by requirements for precise alignment of bolt holes. Easy alignment of connection methods is vital for efficient installation and maintenance. Engineers must opt for standardized connection methods and precision-engineered components that allow pipes to align effortlessly during assembly.

Movement Accommodation

Figure 1: Alignment & Movement Issues



Pipe systems often encounter various forms of movement, including vibrations, 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.

BIM Enablement of DfMA

The concepts of DfMA - Design for Manufacture & Assembly is the foundation of the discussion around 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.

3.2.2 Reliability Considerations (Greater detail in Appendix A)

Verified 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 *"Guidelines for Connection"* 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.

Thermal tolerance: 20 °C to 70 °C - Proximity of TCS fluid to IT chip heat can result in temperatures close to the maximum case temperature of the IT chip, which may be well above normal fluid operating temperature. Connection methods and pipe materials should be rated for full performance at maximum temperature, typically 70 °C, and for movement accommodations over the full temperature range.

3.3 TCS Water-based Fluid Requirements

Guidance for TCS water-based fluid requirements is highlighted in several 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 highlights the following comparison of FWS vs TCS requirements.

Table 2 - ASHRAE TC 9.9 WP: Water-Cooled Servers Common Designs, Components, and Processes

Parameter	FWS	TCS	Units
pH	7 to 9	8.0 to 9.5	
Corrosion inhibitor(s)	Required	Required	
Biocide	–	Required	
Sulfide	<10	<1	ppm
Sulfate	<100	<10	ppm
Chloride	<50	<5	ppm
Bacteria	<1000	<100	CFUs/mL
Total hardness (as CaCO3)	<200	0	ppm
Conductivity	–	0.2 to 20	micromho/cm
Total suspended solids		<3	ppm
Residue after evaporation	<500	<50	ppm
Turbidity	<20	<20	NTU

Key aspects where fluid requirements impact pipe system design include:

- Chemical interaction with pipe material
- Specific heat impact on TCS loop capacity
- Filtration requirements for microchannel heat exchangers and cold plate
- Temperature range requirement

Chemical interaction with pipe material. - Chemicals and glycol can interact with some pipe and gasket materials. Material selection should include evaluation of chemical compatibility, including embrittlement.

Specific heat impact on TCS loop capacity - Water has the highest specific heat of any fluid in common use in data center applications, meaning it can carry more heat per volume than any other fluid. Additives such as glycol generally reduce the specific heat of water (typically <10%), which reduces the cooling capacity of the TCS by the same percentage. Use of water with chemical inhibitors versus water plus glycol is addressed in other documents.

Temperature range requirements - TCS temperature range requirements can vary significantly with application. Rear door heat exchangers have lower temperature ranges than "liquid to chip" solutions, as air is the contact medium in a door heat exchanger, whereas the TCS fluid is in direct contact with the chip.   Maximum chip case temperatures (~90C) can greatly exceed normal operation temperatures, creating a need for maximum TCS fluid design temperatures up to 70C. (https://www.boydcorp.com). Thermal range has a significant impact on pipe movement and pipe strength, especially of non-metallic pipes.

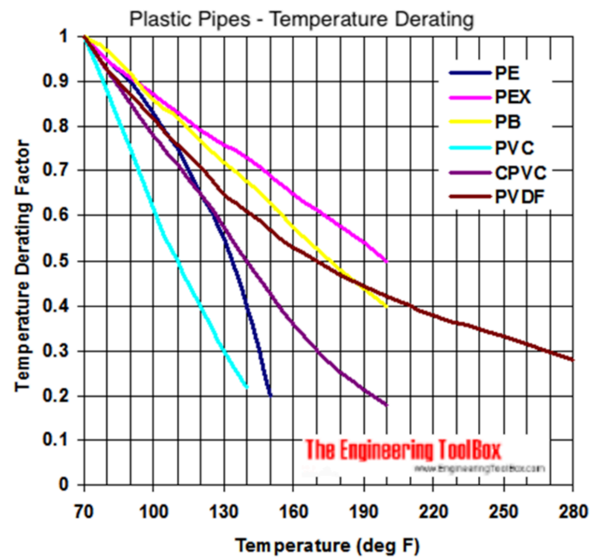
Filtration below 50µm - Filtration requirements also vary with application. "Microchannel heat exchangers" often used in cold plate solutions are driving requirements for **25µm filtration.** Pipe materials that contribute corrosion products (i.e. carbon steel) require careful consideration and are typically avoided. Maintenance procedures (MOPs, SOPs) need to be defined to ensure standard maintenance and operation does not introduce contamination. 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 particles, cleaning chemicals and any waste products from welds and fusion connections. Table 3A summarizes liquid to rack pipe design considerations for temperatures and filtration.

Table 3A Liquid To Rack Pipe Design Considerations

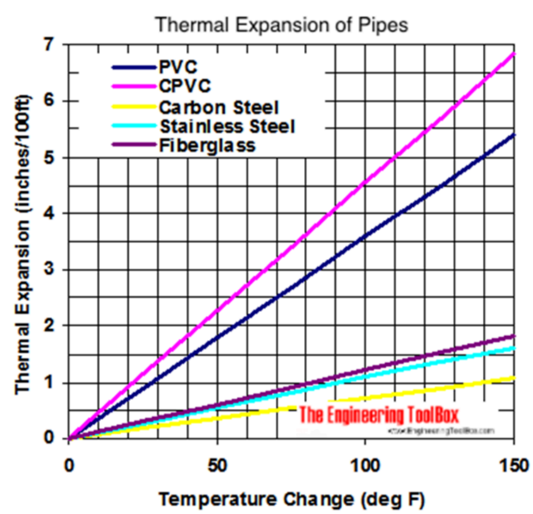
Requirement	Door HX	Liquid To Chip	
		ColdPlate	Other - Rack immersion, 2PL
T max	< 100 F / 35 C	160 F / 70 C	160 F / 70 C
T min	~ 68 F / 20 C	~ 68 F / 20 C	~ 68 F / 20 C
P max	50 PSI, 3.4 Bar	50 PSI, 3.4 Bar	50 PSI, 3.4 Bar
25µ Filtration	Maybe	Yes	Maybe
CDU	TCS CDU Likely	TCS	Integral to Immersion system
Common Pipe Types	Carbon Steel, Stainless Steel, Copper, PPR, CPVC	Stainless	Stainless

3.4 TCS Pipe Selection Considerations

- TCS Water 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



Thermal performance range (20 °C/68 °F-70 °C/158 °F) – TCS proximity to chip temperatures creates a broad temperature band for design consideration. Temperatures at construction are typically around 20 °C/68 °F. Peak temperatures associated with chip temperatures could approach 70 °C/158 °F. Many non-metallic pipe materials see significant degradation in strength above 40 °C/104 °F and require additional support structure.



Thermal movement, (20 °C/68 °F-70 °C/158 °F) – Thermal movement of pipe systems creates several challenges. Pipe system mounting and installation needs to accommodate full range of motion. Pipe connections can become stress points, creating challenges in maintenance and reliability. Operational modularity and circularity is greatly simplified with minimal 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. Metals can become brittle at temperatures well below TCS range. High temperature, chemistry, stress, and age are factors that can lead to embrittlement of some nonmetal pipe materials. Manufacturers should provide data addressing the potential of embrittlement.

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). Lower strength pipe materials have thicker walls, smaller internal diameter, and less area available for flow.

Non-metallic pipes require significantly thicker walls, resulting in reduced internal diameter (flow areas) for given external pipe diameter. In the example shown in Table 3 B, the heat carrying capacity of Nominal Pipe Sizes 3, 4, 6 stainless steel pipe are compared with PPR (SDR 11) and CPVC (Sched 80) showing significant reduction in heat flow capacity due to wall thickness of non-metals.

Table 3 B Pipe Flow Comparison, Stainless vs Non-Metal

Heat Transfer Fluid:	Propylene Glycol 25%	
Specific Heat (Btu/lbm °F):	0.926	
Density (lbm/US gal):	8.609	
ΔT (°F):	18	10 °C
Velocity (ft/s):	7.5	2.3 m/s

		Schedule	Stainless Steel Schedule 10			Schedule	SDR 11				Schedule	Schedule 80			
		Material	Stainless Steel			Material	HDPE High Density Polyethylene				Material	CPVC Chlorinated Polyvinyl Chloride			
Pipe Size (in)	DN (mm)	Cross-Sectional Area (sq. in)	Maximum kW	"Dry" Pipe Weight per Foot (lb/ft)	"Wet" Pipe & Fluid Weight per Foot (lb/ft)	Cross-Sectional Area (sq. in)	Maximum kW	% kW Comparison to Stainless Steel Schedule 10	"Dry" Pipe Weight per Foot (lb/ft)	"Wet" Pipe & Fluid Weight per Foot (lb/ft)	Cross-Sectional Area (sq. in)	Maximum kW	% kW Comparison to Stainless Steel Schedule 10	"Dry" Pipe Weight per Foot (lb/ft)	"Wet" Pipe & Fluid Weight per Foot (lb/ft)
3	80	8.35	492	4.4	8.2	6.44	380	77%	1.5	4.4	6.61	390	79%	2.0	5.0
4	100	14.25	841	5.7	12.1	10.65	628	75%	2.4	7.2	11.50	678	81%	3.0	8.1
6	150	31.74	1872	9.5	23.7	23.08	1361	73%	5.3	15.6	26.07	1538	82%	5.7	17.3

Carbon Footprint (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, non-metallic pipes typically do not incorporate recycled materials, primarily because the quality of recycled materials often falls short of that of new, raw materials.

When assessing the full scope of a product's carbon footprint, it's crucial to consider the impact of material reuse. However, data quality and availability supporting carbon footprint comparisons is limited and varies greatly depending on the type of pipe and its manufacturer. 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 CO_2 footprint, as well as how their carbon footprint changes when recycled content is included. This comparison underscores how recycled content can significantly influence the carbon footprint of metallic pipes.

Table 4: Full Scope CO2 Footprint - Stainless Steel vs HDPE vs PPR

	Internal Diameter used for comparisons (mm)			304L Stainless OD=168.mm		SDR11 HDPE OD=200mm		PPR SDR 11 OD=200mm	
NPS	Stainless Sched 5	HDPE	PPR	CO2 A1-A3 (Kg/lm)	C02 Full Scope (Kg/lm)	CO2 A1-A3 (Kg/lm)	C02 Full Scope (Kg/lm)	CO2 A1-A3 (Kg/lm)	C02 Full Scope (Kg/lm)
6" DN150	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

Note - the intent of this comparison is simply to demonstrate that carbon footprint varies significantly with recycled content and 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. Stainless steel is substantially lower cost than copper pipe.

Table 5: Sample Price Comparison, SS vs Copper

20ft	207994	3X20 L HARD COPPER TUBE	28.477/ft	569.54
20ft	206180	4X20 L HARD COPPER TUBE	47.682/ft	953.64
20ft	1913985	3IN S10 304L A312 SS PIPE IMP	12.742/ft	254.84
20ft	1913988	4IN S10 304L A312 SS PIPE IMP	16.500/ft	330.00
		TAXES NOT INCLUDED		

Cost estimate provide by All-Tex Pipe & Supply (Dallas, TX) April 2024

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 hours associated with pipe, branch lines, and connection method.
- 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.

3.5 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. However, many liquid cooling solutions only capture a fraction of the total heat, the rest of the heat is captured by computer room air-handlers (CRAH) or other air-cooling systems.

Different cooling methods have different levels of heat capture by the liquid. Liquid cooling systems do not capture all the heat generated by IT equipment and will need to be supplemented with air cooling systems. 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. In that situation, the TCS system would need to be sized within 80% of the electrical load to support TCS cooling requirements.

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.

For example:

- 1200 Amp Busway (@ 415V-3φ, unity pf) $\simeq$ 860 KW
- 4” Stainless Pipe (PG25 @ ΔT=15℉/8℃) $\simeq$ 773 KW (estimate based on flow, specific heat)
  - 80% of 860 KW = 688 KW => 4” pipe

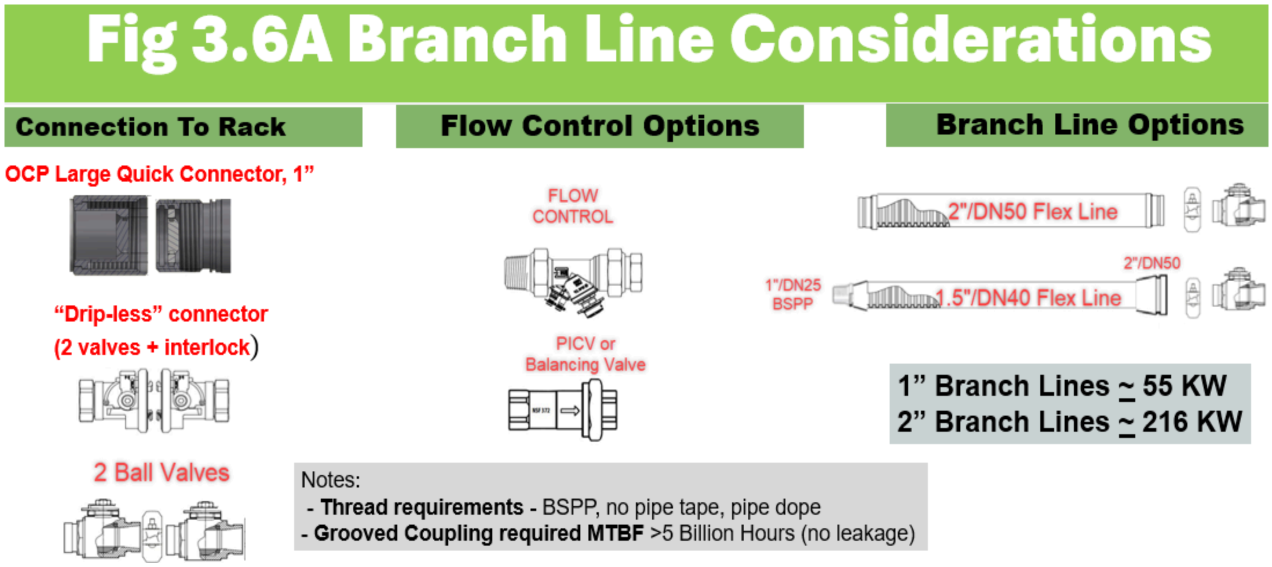
Combinations of cooling methodologies will be necessary in facilities supporting liquid cooled IT. There will always be some component of heat escaping to the data center environment and air cooling of the IT environment will still be a significant consideration even in a data center filled with “liquid 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 in data centers to capture the heat 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.

3.6 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:



- **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.

- **Flex Line :** 1" branch lines max capacity ~ 60 KW/rack , 2"/DN 50 branch lines max capacity ~ 220 KW/rack (@ ΔT = 18 °F/10 °C, flow = 7.5 fps, 2.3 m/s)

- **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 and simplifies the continued operation of the IT rack from an alternate cooling loop when one of the cooling loops needs to be shut down and drained for maintenance. This arrangement is analogous to the use of dual power supplies to the IT rack that can be independently isolated and maintained while the rack continues to operate.

Cleanliness and leak avoidance requirements for the TCS create a need for pre-assembled, cleaned, tested branch lines with a common connection method to IT systems. Filtration requirements of 25 micron are difficult to achieve with job-site construction as practices such as pipe tape and pipe dope are prohibited in the TCS system. Risk of galvanic corrosion can be greatly reduced by integrated design approaches for headers and branch lines, reducing the need for job-site evaluation of components. Flow and heat (KW) capacity validation is also simplified with modular pretested branch lines.

Balancing and Flow Control Considerations: Proper balancing and flow control is a critical function of the branch line, with impact on system efficiency and performance. Use and benefits of automated flow control vs manual control valves, flow setters, and active flow adjustment systems to be addressed in future revision.

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). 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, draining the IT rack, disconnecting the drained IT rack from the branch line(s), and then removing the drained IT rack.

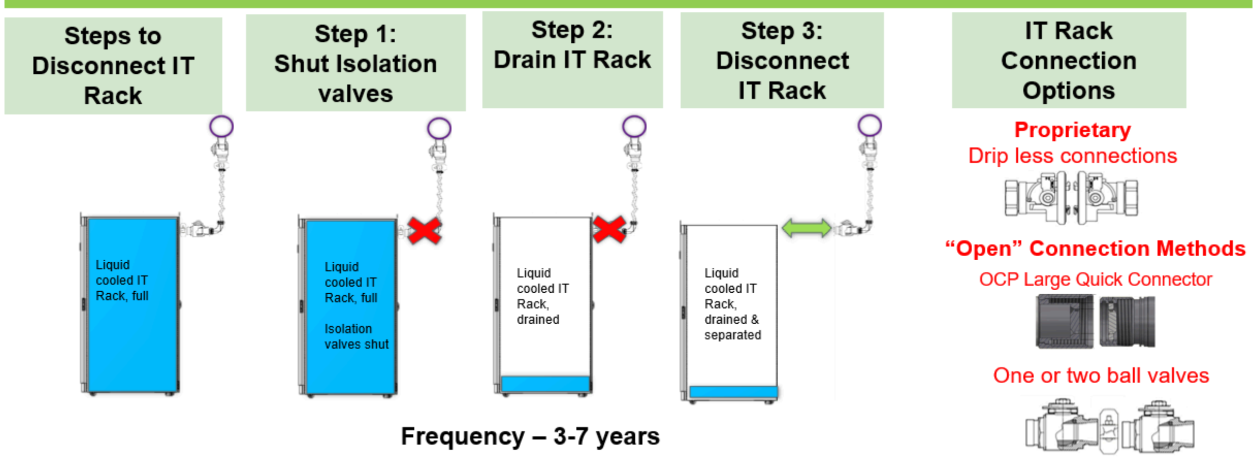


Fig 3.6B Connection Considerations: IT rack to TCS

The connection/disconnection method between the branch line and the IT Rack requires due consideration for reliability, simplicity, cost, head-loss and global availability. For concurrent maintainability outside the IT rack, each of the liquid branch lines, headers, and their components must be able to be shut down, drained, and replaced or maintained without affecting the delivery of cooling liquid via another branch / header pair.

Methods under consideration for IT rack connection include both "open" connection methods - not restricted by intellectual property constraints, and proprietary "drip less" methods. "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.
- **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.
- **Single Isolation Valve Methods –** For top of rack connections, a simple isolation valve and coupling device, combined with standardized procedure (MOP or SOP), may provide optimum protection without the supply chain challenge of proprietary drip-less connection methods.

Proprietary IT rack connection methods include:

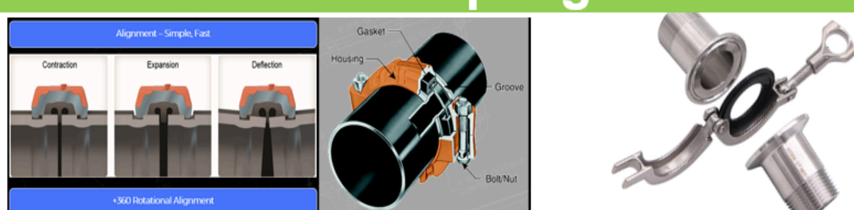
- **"Drip less" Interlocked connectors**. A typical "drip less" connector used for IT racks uses two isolation valves with an interlock designed to minimize dripping and leakage. "Drip less" connectors are proprietary products, with limited global availability above 1"/DN25.

BSPP Thread connection - 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 (AWWA 606) - *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. Use of couplings with MTBF > 5 billion hours is recommended for TCS and branch line assemblies. Movement accommodation on header sections can be accommodated by use of flexible couplings.

Tri-Clamp Connections (DIN-32676 specification)- Tri-clamp connections used in the food and beverage industry are also under consideration. Variety of tri-clamp products are available. Due to the critical nature of TCS systems and high cost of leakage, MTBF> 5 billion hours is recommended. Also, on rigid pipe sections such as the header, movement accommodation (axial and angular) needs to be addressed.

Fig 3.6C – Grooved Coupling Vs Tri-Clamp



	Grooved Coupling	Sanitary Tri-Clamp
Application	Primarily used in industrial piping systems, especially in HVAC, plumbing, fire protection, and mission critical applications.	Commonly used in the food, beverage, pharmaceutical, and biotech industries where frequent disassembly and cleaning needed
Installation	Coupling placed over the grooved ends of two pipes, 2 bolts tightened, compressing gasket and to seating housing into grooves.	Ferrels are attached to the ends of two pipes - threaded, brazed or welded. Tri-clamp placed over ferrels, locked with wing-nut
Movement accomodation	Flexible coupling mitigates vibration & alignment stress. Allows movement	Rigid connection
MTBF, Mission Critical Design	MTBF >> 7 Billion Hours, design life > 40 years	Varies

Note 1: MTBF >>7 Billion hours based on Victaulic study of 18 data center projects, >150,000 couplings, over 13 year period (2011-2024) with no issues

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.

IT Rack Installation & Removal Operational Considerations

- Considerations for site-level flushing, cleaning and commissioning:
- Connection of F&R flexible hoses together to allow for flushing of completed system.
- Consider incorporation of a regulating valve into the bypass connection to impose a false resistance equivalent to that of the rack + manifolds, etc. This will allow CDU flow proving and commissioning and PIC valves on final connections to racks to be calibrated and pre-set prior to connection of racks. Racks may not all be installed at the same time and could be deployed in phases.

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 well in excess of 60 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 can transport approximately 55 KW of heat (@ΔT= 18°F, 10°C). A 2”/DN50 branch line can support approximately 220KW. While most application requirements today are under 60 KW/rack, projections of IT rack densities up to and beyond 200 KW are becoming more common, requiring use of multiple 1”/DN25 lines.

- **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. Use of dual ball valve connection methods need to be clearly defined in an SOP/MOP.

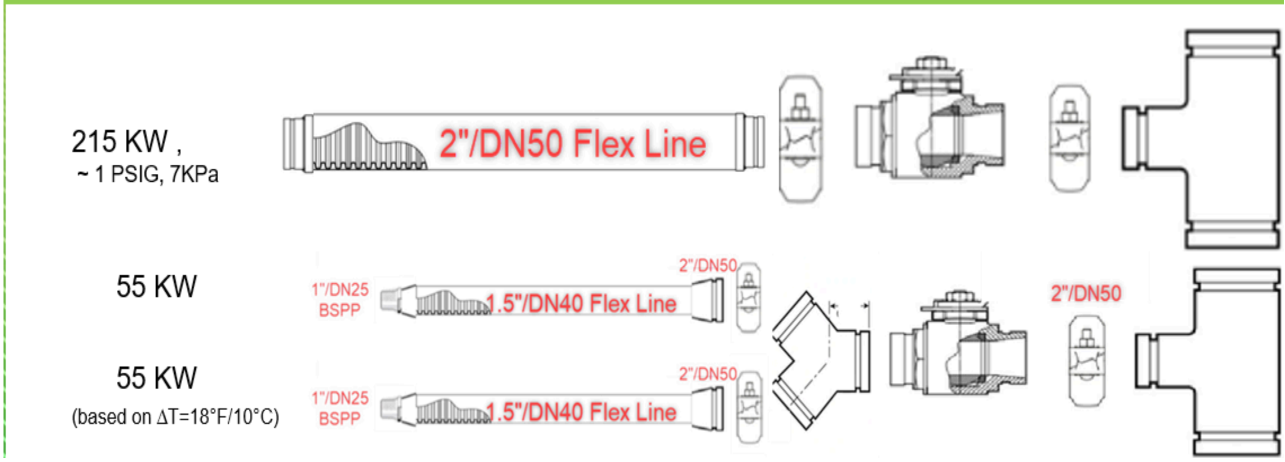
- **Supply Chain:** Availability of proprietary “drip less” connections over 1”/DN25 is limited and inconsistent. While availability will eventually increase, dependence on proprietary connection methodologies will continue to create supply, cost and compatibility challenges.

- **Pressure drop:** Multiple smaller connections create more challenges in pressure drop and flow balancing. Pressure drop across 1”/DN25 lines can be over five times higher than 2”/DN50 lines, with impact on CDU pump sizing and performance, and energy usage. Use of larger (1.5”/DN40) lines with 1”/DN25 connectors reduces pressure drop but does not increase capacity.

Multiple 1”/DN25 Connections vs Single 2”/DN50 Connection

Use of a 2”/DN50 tap supports ability to cool racks up to 215 KW capacity (based on ΔT= 18℉/10℃). Supplying the IT rack with a 2”/DN50 flex line or multiple 1”/DN25 flex lines are depicted in Fig 3.6C. As an example of the “new wave” of liquid cooled IT, the NVIDIA GB200 DGX Superpod exceeds 120KW/rack, requiring either a single 2”/DN50 line or multiple 1”/DN25 lines.

Fig 3.6D Single Valve Train vs Multi Valve Train



4. Conclusion

The escalating demand for liquid-cooled IT systems without clarity in thermal parameters and power densities necessitates advancements in design and delivery processes. To accommodate this burgeoning need, it is crucial to innovate in liquid distribution systems, so they are adaptable, resource-efficient, and sustainable throughout the data center's lifespan.

A modular approach to the design, manufacture, and installation of Technology Cooling System (TCS) piping, including headers and branch lines, effectively meets these demands. This modularization not only fosters adaptability and aligns with resource and sustainability goals, but also mitigates many challenges in fabrication and global supply chain. By assembling modules off-site, we can enhance pipe cleanliness, streamline the supply chain, reduce defects and risks, and leverage economies of scale to lower costs.

For successful development of modular TCS systems, certain key requirements must be met. These include minimal thermal movement, easy alignment of connection methods, and accommodating pipe movement over the life of the data center. Furthermore, these connection methods must be reliable and concurrently maintainable. Additionally, simplifying the process for digital design and delivery, such as through Building Information Modeling (BIM) for module definition, is critical.

In conclusion, developing TCS modules that align with these criteria of constructability, reliability, and digital design & delivery will significantly increase the ability to meet the challenges of adaptability, cleanliness, and global supply chain demands. This approach not only reduces risks but also enhances overall sustainability, paving the way for a more efficient and effective deployment 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 US Non-Profit professional organization that develops standards and guidelines for HVAC systems.
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.
Dripless connectors	A type of pluggable liquid connector which eliminates drips and is able to withstand long term use.
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 dissipate heat.
IT (Information Technology)	Refer to "Information Technology"
ITE (Information Technology Equipment)	Refer to "Information Technology Equipment"
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
Primary Coolant	The fluid that is in direct contact with the heat-generating components in a cooling system, responsible for absorbing and transferring heat away from those components.
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 an immersion system 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

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9. Appendices

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.

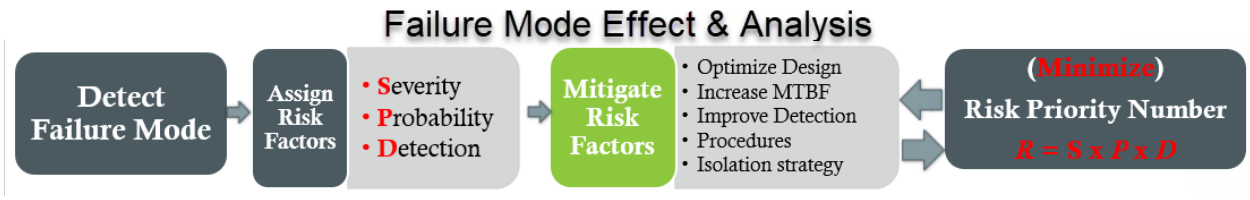
Figure A-1: Data center risk assessment framework (source: DCMETRIX)

The expectation is that manufacturers perform Failure Mode and Effect Analysis (FMEAs) to reduce the severity and probability and increase detectability of failures and associated risk.

FMEA: The first step is identifying failure modes, then assigning risk factors (severity, probability, detection) which combine to create a Risk Priority Number (RPN). A variety of actions can then be taken to reduce the RPN by reducing the risk factors and increasing detection w:

- **Severity:** change design to reduce severity of failure mode
- **Probability**: use components or methods with higher reliability and ability to verify proper installation.
- **Detection**: integrate detection methods or technologies (i.e. leak detectors & visual detection)
- **Procedures**: Many risks can be avoided by defining procedures and precautions. (MOPs, SOPs, and EOPs)

The TCS by its very nature requires FMEA review: running water pipes in the vicinity of ITE requires risk management (note - this discussion was also addressed in OCP ACF whitepaper on Reference Designs and Best Practices).



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:

Table A1: Inspection Methods of Pipe Connections

	Inspection Method to Prevent	
	Leakage	Failure
ReConnection Methods		
Threaded	None	Visual
Flange	Torque check	Torque check
Grooved Coupling*	Visual	Visual
Fixed Connection Methods		
Weld	X-Ray	X-Ray
Crimped/pressed	???	???
Fused	???	???

OCP WP - GUIDELINES FOR CONNECTION OF LIQUID COOLED ITE

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 3.5 billion hours is needed to reduce the need for extensive use of leak detection, collection and protection.

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 > 5 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 7 billion hours. (One issue occurred with a coupling that was not verified properly installed and was correspondingly not included in the study). As previously mentioned, verification of proper installation is required for MTBF analysis.

Table A2 Reliability of Properly Inspected Mission Critical Rated Couplings

Over 7.1 Billion Hours MTBF – With No "F" Visual Inspection = No Failures				
Data Center	**Location**	**Year**	**# of Couplings**	**Coupling Hours**
[Colo Provider]	Cork	2011	1,750	201,810,000
[Colo Provider]	Frankfurt	2012	3,886	413,998,896
Telefonica	Madrid	2012	25,000	2,662,800,000
Green Mountain	Rennesoy	2013	7,000	684,432,000
Telecity / Digital	Amsterdam	2016	2,712	193,832,064
[Colo Provider]	Quincy, WA	2019	1,834	82,882,128
Global Switch	Hong Kong	2019	19,000	858,648,000
[Colo Provider]	Dublin	2020	3,100	112,864,800
[Colo Provider]	Marseilles	2020	20,000	728,160,000
[Colo Provider]	Africa	2020	9,700	353,157,600
[Cloud Provider]	Quincy, WA	2021	1,301	35,938,824
[Colo Provider]	Malaysia	2022	26,195	494,771,160
[Colo Provider]	Dublin	2023	3,200	32,409,600
[Colo Provider]	Los Angeles, CA	2023	1,201	12,163,728
[Colo Provider]	Quincy, WA	2023	1,550	15,698,400
[Colo Provider]	Phoenix, AZ	2023	3,891	39,408,048
[Colo Provider]	Hillsboro, OR	2023	5,638	57,101,664
[Colo Provider]	Malaysia	2023	13,130	132,980,640
As of Date:	**# of couplings evaluated**		**150,088**	
	hours of coupling service evaluated			**7,113,057,552**
8/1/2024	**# of issues with proper installation**			**0**
	# of issues with improper installation/not inspected			**1**

Data provided by Victaulic, "Reliability of Victaulic Couplings in Data Centers"

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.

For connection methods where proper installation can be visually verified, **photographic verification** adds an even higher level of auditability and reliability, significantly reducing risk for connections that are not readily available for re-inspection. or in areas of high severity risk. Integration of photographic inspection to drawings or construction schedules can be simplified with an “app”:

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 fairly 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.

The heat transfer formula for fluid flow is Q = m * Cp * ΔT, where:

- Q: Heat energy in Joules or Btu
- m: Mass of the substance in kilograms or pounds
- Cp: 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 1: Estimating CDU & TCS Loop capacity:

Estimating CDU & TCS loop capacity: For many data centers, "provisioning for liquid cooled IT" equates to having pipe taps available. Estimating loop capacity for a given pipe size (or pipe type) has many variables on the FWS side including fluid (i.e water + glycol), ΔT, flow velocity, and pipe size (internal diameter).

Simple calculator tools can help rapidly estimate this requirement. For example, calculating maximum cooling load for given pipe type & size can be quickly estimated using a tool that incorporates data tables of specific heats of fluids, pipe schedules (internal diameters), and allows inputs of velocity and temperature (rise ΔT)

Pipe & Load Calculations

Calculate Required Pipe Size For Cooling Load

Heat Transfer Fluid:	Water		
		Specific Heat (Btu/lbm °F)	1.000
		Density (lbm/US gal):	8.345
Cooling (MW):	6.000		
		Cooling (tons):	1,706
		Cooling (Btu/h):	20,472,850
Delta T (F):	14	Detla T (C):	8.0
		Flow Rate (gpm):	2,921
		Flow Rate (l/s):	184.3
Velocity (ft/sec):	8	Velocity (m/s):	14.6
		Min. Pipe I.D. (in):	12.052
Pipe Schedule:	Stainless Steel Schedule 10		
Pipe Size (in):	12	Pipe Size (mm):	DN 300
		Pipe O.D. (in):	12.750
		Pipe Thickness (in):	0.180
		Pipe I.D. (in):	12.390

Calculate Maximum Cooling Load For Pipe Size

<----------- Select On Left Size		Heat Transfer Fluid:	Water
		Specific Heat (Btu/lbm °F)	1.000
		Density (lbm/US gal):	8.345
Pipe Schedule:	Stainless Steel Schedule 10		
Pipe Size (in):	12	Pipe Size (mm):	DN 300
		Pipe O.D. (in):	12.750
		Pipe Thickness (in):	0.180
		Pipe I.D. (in):	12.390
		Cross-section Area (sq. in)	120.57
Velocity (ft/sec):	8	Velocity (m/s):	14.6
		Flow Rate (gpm):	3,006
		Flow Rate (l/s):	189.7
Detla T (F):	14	Detla T (C):	8.0
		Cooling (Btu/h):	21,074,144
		Cooling (tons):	1,756
		Cooling (MW):	6.176

Example 2: Estimating loop capacity, racks per loop, branch line capacity

In a similar manner, evaluating TCS loop capacity and branch line capacity for a variety of pipe types, pipe sizes, fluid types, flow ranges, and temperature ranges can be estimated in seconds.

In Fig B-1, comparing 4"/DN100 with 1"DN25 Branch Line with 6"/DN150 with 2"/DN50 branch lines

4"/DN100: Loop Capacity = 840 KW / loop. Branch line capacity (1"/DN25) = 55KW / line

6"/DN150: Loop Capacity = 1872 KW /Loop. Branch line capacity (2"/DN50) = 215KW/ line

(flow= 7.5 FPS, 25% Polyglycol PG 25 @ ΔT=18F/10C),

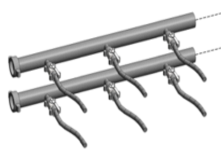
Increasing ΔT to 20C doubles the capacity of the branch line (loop capacity still determined by CDU capacity)

Fig B-1: Modular Selector Tool – Capacity Comparison

4"/DN100 Header, 1"/DN25 Branch Line VS 6"/DN150 Header 2"/DN50 Branch Line

4"/DN100 SS Header ~ 840KW 1"/DN25 Branch Line ~ 55KW

Pipe Schedule:	Stainless Steel Schedule 10	
Heat Transfer Fluid:	Propylene Glycol 25%	
Specific Heat (Btu/lbm °F):	0.926	
Density (lbm/US gal):	8.609	
Velocity (ft/s):	7.5	2.3 m/s
Header Pipe Size (in):	4	DN 100
Branch Pipe Size (in):	1	DN 25



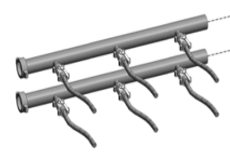
	Pipe Size (in)	Pipe O.D. (in)	Pipe Wall Thickness (in)	Pipe I.D. (in)	Cross-Sec. Area (sq. in)	Flow Rate at 7.5 ft/s (gpm)	(l/m)	(l/s)
Header	4	4.500	0.120	4.260	14.253	333	1,261	21.0
Branch	1	1.315	0.109	1.097	0.945	22	84	1.4

ΔT (°F)	(°C)	Max Row kW at 7.5 ft/s (kW)	Max Rack kW at 7.5 ft/s (kW)	Maximum Number of Racks per Row: 50 kW per Rack	75 kW per Rack	100 kW per Rack	125 kW per Rack	200 kW per Rack
14	7.8	654	43.4	-	-	-	-	-
18	10.0	841	55.8	16	-	-	-	-
27	15.0	1,261	83.6	25	16	-	-	-
36	20.0	1,681	111.5	33	22	16	-	-

NOTE: All calculations are for illustration purposes only and are not to be the basis of design.

6"/DN150 SS Header ~ 1872 KW 2"/DN50 Branch Line ~ 215KW

Pipe Schedule:	Stainless Steel Schedule 10	
Heat Transfer Fluid:	Propylene Glycol 25%	
Specific Heat (Btu/lbm °F):	0.926	
Density (lbm/US gal):	8.609	
Velocity (ft/s):	7.5	2.3 m/s
Header Pipe Size (in):	6	DN 150
Branch Pipe Size (in):	2	DN 50



	Pipe Size (in)	Pipe O.D. (in)	Pipe Wall Thickness (in)	Pipe I.D. (in)	Cross-Sec. Area (sq. in)	Flow Rate at 7.5 ft/s (gpm)	(l/m)	(l/s)
Header	6	6.625	0.134	6.357	31.739	742	2,809	46.8
Branch	2	2.375	0.109	2.157	3.654	85	323	5.4

ΔT (°F)	(°C)	Max Row kW at 7.5 ft/s (kW)	Max Rack kW at 7.5 ft/s (kW)	Maximum Number of Racks per Row: 50 kW per Rack	75 kW per Rack	100 kW per Rack	125 kW per Rack	200 kW per Rack
14	7.8	1,456	167.6	29	19	14	11	-
18	10.0	1,872	215.5	37	24	18	14	9
27	15.0	2,808	323.3	56	37	28	22	14
36	20.0	3,744	431.1	74	49	37	29	18

NOTE: All calculations are for illustration purposes only and are not to be the basis of design.

Example 3: Performance comparison, different pipe types: Comparing weight and flow capacity of pipe material types can be greatly simplified with design tools. Figure B-2 shows ~ 17% reduction in flow capacity of copper vs thin wall stainless steel for similar weights.

Fig B-2: Flow Comparison, SS vs Copper

Heat Transfer Fluid:	Propylene Glycol 25%	
Specific Heat (Btu/lbm °F):	0.926	
Density (lbm/US gal):	8.609	
ΔT (°F):	18	10 °C
Velocity (ft/s):	7.5	2.3 m/s

		Schedule	Stainless Steel Schedule 5			Schedule	CTS Type L			
		Material	Stainless Steel			Material	Copper			
Pipe Size (in)	DN (mm)	Cross-Sectional Area (sq. in)	Maximum kW	"Dry" Pipe Weight per Foot (lb/ft)	"Wet" Pipe & Fluid Weight per Foot (lb/ft)	Cross-Sectional Area (sq. in)	Maximum kW	% kW Comparison to Stainless Steel Schedule 5	"Dry" Pipe Weight per Foot (lb/ft)	"Wet" Pipe & Fluid Weight per Foot (lb/ft)
3	80	8.73	515	3.1	7.0	6.81	402	78%	3.3	6.4
4	100	14.75	870	4.0	10.6	11.93	704	81%	5.6	10.9
6	150	32.24	1902	7.8	22.2	26.83	1583	83%	10.2	22.2
8	200	55.51	3274	10.2	35.0	46.87	2765	84%	19.3	40.3

Appendix C: Impact of 25µm Filtration on Design, Construction, Operation, Maintenance

(Excerpts from OVH Cloud guidance document)

Successful evaluation and deployment of 25-micron filtration in the TCS has been shared by OVHcloud. While these methods may not be applicable to all designs, a meticulous analysis of the challenges encountered in the early stages serves as foundation for providing insights into makeup water filtration, aiming to enhance overall system performance. The commissioning process is also explored, with a particular emphasis on utilizing a 25-micron mobile filter/pump skid. Below, you'll find a comparative analysis outlining the advantages associated with both parallel and series filter configurations. Furthermore, OVHcloud investigates the strategic placement of filters at both CDU and rack levels, taking into account the potential implications of these choices.

25-micron design allows for finer filtration, effectively capturing smaller particles and contaminants in the water, leading to a higher level of filtration precision, therefore, avoiding eventual further clogging that could occur, impact and damage various components within the loop. It is recommended to filter the makeup water down to 1-micron when possible, to lower the risks as much as possible.

The commissioning process can be done in 2 steps:

1. Flushing and filtering the fluid inside the loop to have it as clean as possible before filling the circuit again

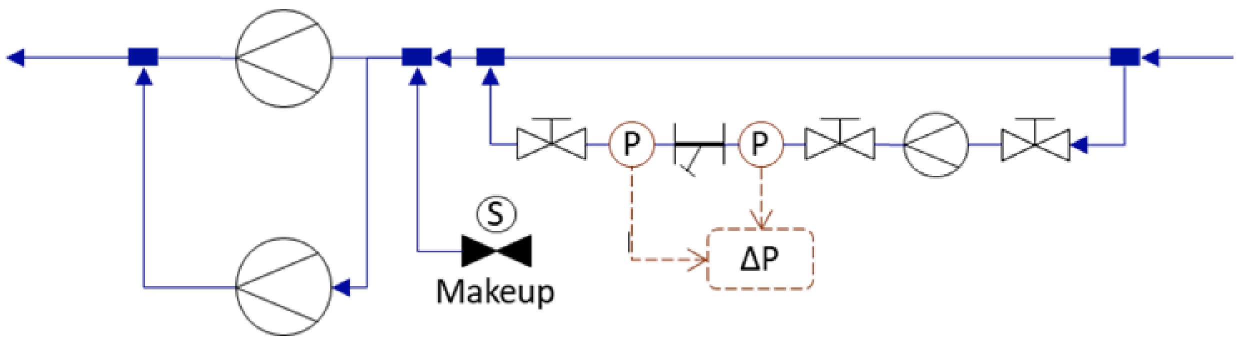
2. Partitioning the loop in order to install an auxiliary 25 µm mobile filter/pump skid for the filling process

Amongst various system filter types and locations possible, the following ones, that have been or are still in use at OVHcloud, are worth mentioning. Two strategic locations have been chosen - one at the cooling module level, and one at the rack level.

At the Cooling Module (main IT Shelter CDU) level that distributes the flow to all racks, there could be two configurations in terms of filter positioning, with each one having its own advantages and disadvantages.

The parallel filter set:

In this configuration, a set of small filters and a circulator for a predefined flow is to be installed in parallel to the main circuit as shown in the figure below. The circulator is mandatory in this configuration in order to counterbalance the pressure drop resulting from the addition of the filter, valves and pressure sensors. The flow rate of the pump is to be defined accordingly to the latter.



Depending on the design configuration, the filter set could be installed before or after the pumps based on what's preferred and is more convenient.

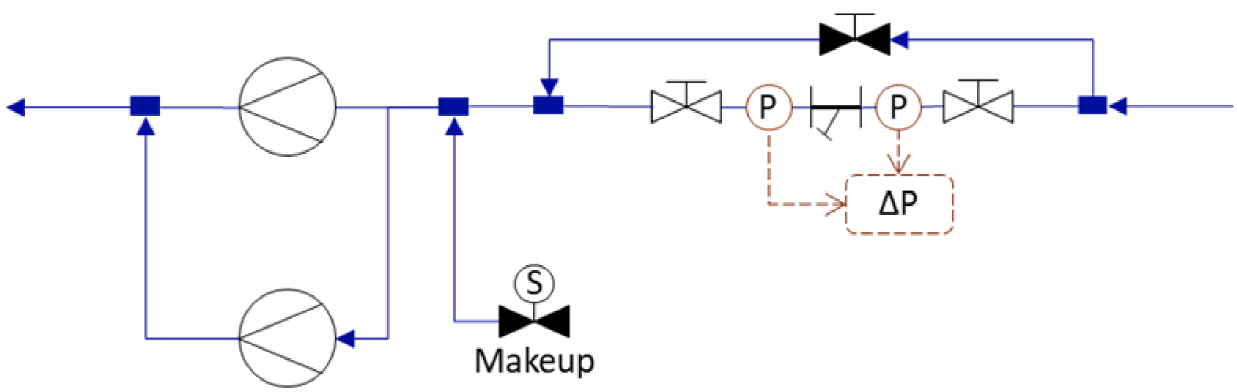
In this configuration, the inclusion of the filter set generates no additional pressure drop in the loop. Which also helps keeping a low power consumption per circulator, making this configuration cost-effective overall. On top of that, the design is quite compact and can be integrated easily within different types of loops.

On the other hand, the filtering efficiency of this filter set is not the highest since a part of the flow is always bypassing the filter. This makes the filtering process quite slow compared to other configurations where the whole flow passes through the filter.

OVHcloud used such configuration a few years ago within infrastructures with low ΔT of 5°C when flow rates used to be high and additional pressure drop in the loop could not be accepted.

The series filter set:

Another configuration that leads to a more efficient filtering, is the one where the filter set is in series within the loop as illustrated in the figure below. Just like the parallel configuration, the filter set can be installed before or after the pumps depending on the design and different eventual constraints.



In this case, the filtering process is much more effective than in the case of the parallel configuration since the whole flow must pass through the filter set. However, this design generates a higher pressure drop for the same reason, therefore making it more expensive since the power consumption is relatively higher. Nonetheless, if the flow rate is relatively small, for example in the case of a setup operating at high ΔT of 20°C, the pressure drops, power consumption and the operating expenses could be reduced, hence making this solution a good compromise. It should not be forgotten that this design is also quite bulky compared to the parallel one.

OVHcloud has been using such configuration on its recent infrastructures, since they operate at high ΔT of 20°C and running at low flow rates, thus taking advantage of all the benefits of this configuration.

Another key location for the filter set is at the rack level. In this configuration filters are to be distributed in series over the racks at their entrance. Depending on how the filter set is dimensioned, low pressure drops can be reached. The design is more compact with this configuration compared to the previous ones mentioned above.

On the other hand, due to the higher number of filter sets, the cost is notably higher. The filtering performance is not as high as the other cases either. More maintenance is to be expected as well since the number of the involved components is significantly higher.

OVHcloud already implemented this configuration and abandoned it later on due to the high number of inconveniences.

On top of the mentioned configurations and their respective descriptions, there are additional considerations and fine-tuning that could be considered for optimal performance as well.

It is for example important to incorporate pressure sensors in the filtration system, one before the filter, one after it, to have real-time data acquisition which can help for early issue detection by calculating pressure drop over the filter and therefore indicating if the latter has been fouled or not. This can help implement a preventive and predictive maintenance program.

Another non-exhaustive example is the addition of a bypass mechanism. This can turn out to be essential in order to ensure system flexibility and minimizing downtime. Indeed, a bypass mechanism is very handy when it comes to general maintenance and filter replacement operations, during which, the impact on the other components will be inexistant.

Appendix D: Flow Control Considerations

To talk about control, let's talk a bit about the system that we are trying to control. The system starts from the CDU and ends at the rack including the piping and the connection. Although we started designing this system considering a fixed number of racks, this is not necessarily always true. The number of racks can vary depending on specific deployment strategy and rack power density. Thus, the controller should be adaptable to make sure enough liquid flow is delivered to any given rack.

As a starting point, we should know what the flow rate is needed for each rack to be effectively cooled and we should understand the pressure drop associated with this flow rate (the pressure drop here includes the connection from supply and return pipes all the way to the rack including all valve and hoses that help in the connection).

Now, understanding this pressure drop and estimating the pressure drop through the supply and return pipes, the CDU speed should be regulated to deliver the flow required by the rack at that pressure. This will be the set pressure drop for the whole system.
Upon adding and removing racks, the pump will regulate its speed to match the set pressure and thus deliver more or less flow to meet the requirement of the rack or racks.

Next, we have to make sure that the flow per rack meets the design requirement so it won't create unbalanced pressure (some valves might exceed the gauge pressure at high flow), for that reason on each drop, we will use a flow control valve. There are different flavors for this flow control valve (some come as pressure control valves): some of these are manual, some are automatic, some have telemetry capabilities, and some have control capabilities.

The pros and cons of control methodologies (manual, automatic & use of telemetry) is a complex discussion beyond the scope of this paper. As the cold-plate technologies evolve, the benefits of control methodology also evolve and may be suitable for future workstream discussions.

Appendix E: Considerations for TCS Module Size & Valving

The selection of the TCS (Thermal Containment System) 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.

There are two conceptual approaches in use of isolation valves with TCS modules:

- **TCS modules with isolation valves at each end:**

- ***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.

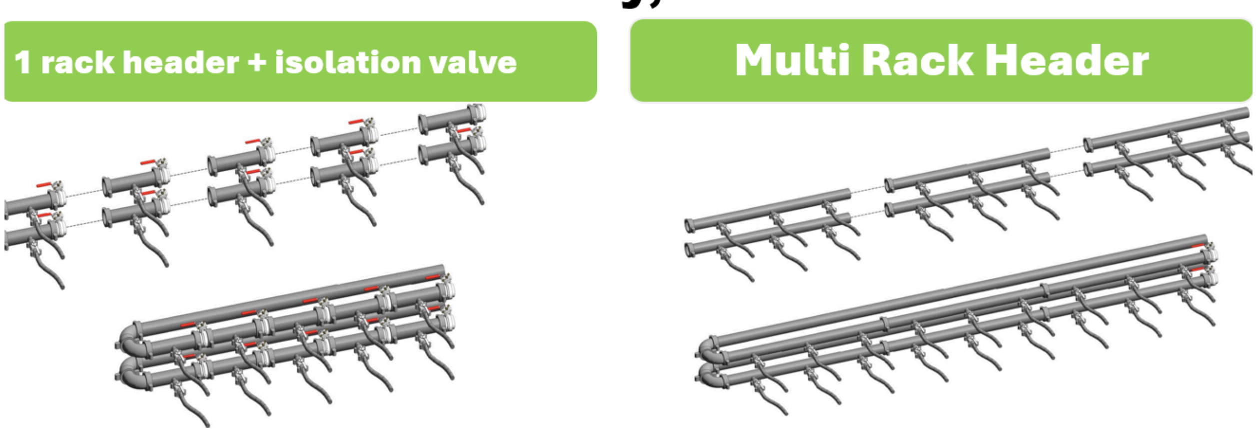
- **Multiple TCS Modules, with isolation valves at the ends of the headers:**
  - ***Lower Cost:*** This option tends to be more cost-effective.
  - ***Header Maintenance Impact:*** However, it requires a shutdown of the entire header during maintenance.

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

Examples of multiple header and TCS module options shown below, with both single rack modules and multiple rack modules. Adopting the approach that the supply is above and the return below, and that the piping is connected to a CDU at either end in each case, we can see that:

- The valves in the supply and return lines on the left allow for either CDU to serve the ITE, but the use of a single valve between branch lines means that maintaining the valve itself impacts an adjacent pair of branch lines. ITE connected to that pair would need to be offline for that maintenance task. To limit the “blast radius “ of a single valve maintenance task to a single branch line, two valves are required between each branch line. If the objective is concurrent maintainability with all branch lines able to service their ITE, this scheme cannot achieve that as shown.
- There are no valves in the supply and return lines on the right, so any maintenance of a part of the supply or return loop removes cooling flow to all the branches shown.
- If the objective is concurrent maintainability with all branch lines able to service their ITE, the scheme on the right can achieve this if the A and B supply and return lines are duplicated.

Fig E-1: Modular Approach to Concurrent Maintainability, “Blast Radius”



Appendix F: Structural Considerations for Deployment of TCS Modules

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

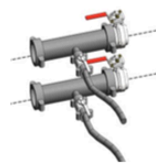
Overhead Pipe Distribution Structural Considerations & Design Options:
When installing pipe systems above data center racks, there are several key structural considerations to ensure the safety and functionality of the installation. These considerations include:

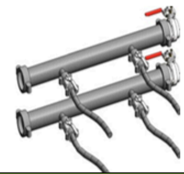
- **Facility Rating:** Check the data center's facility rating; that is, the extent to which it is required to continue to operate after a seismic event. Referred to as Occupancy Category (ASCE 7-05) or similar terms (depending on jurisdiction), most data centers need to continue to operate and are Occupancy 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 - consider weight of liquid cooled IT rack versus air cooled IT racks
- Fig F.1 provides loading estimates of stainless pipe & valving per foot. Figure F.2 provides estimates of weight per module.

Figure F.1 Pipe Weight + Valve Weight Estimation - Stainless Steel Sched 10 Fluid = PG25

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										

Figure F.2: Weight of 1 Rack, 2 Rack Modules, Case 1 (Stainless, PG25)





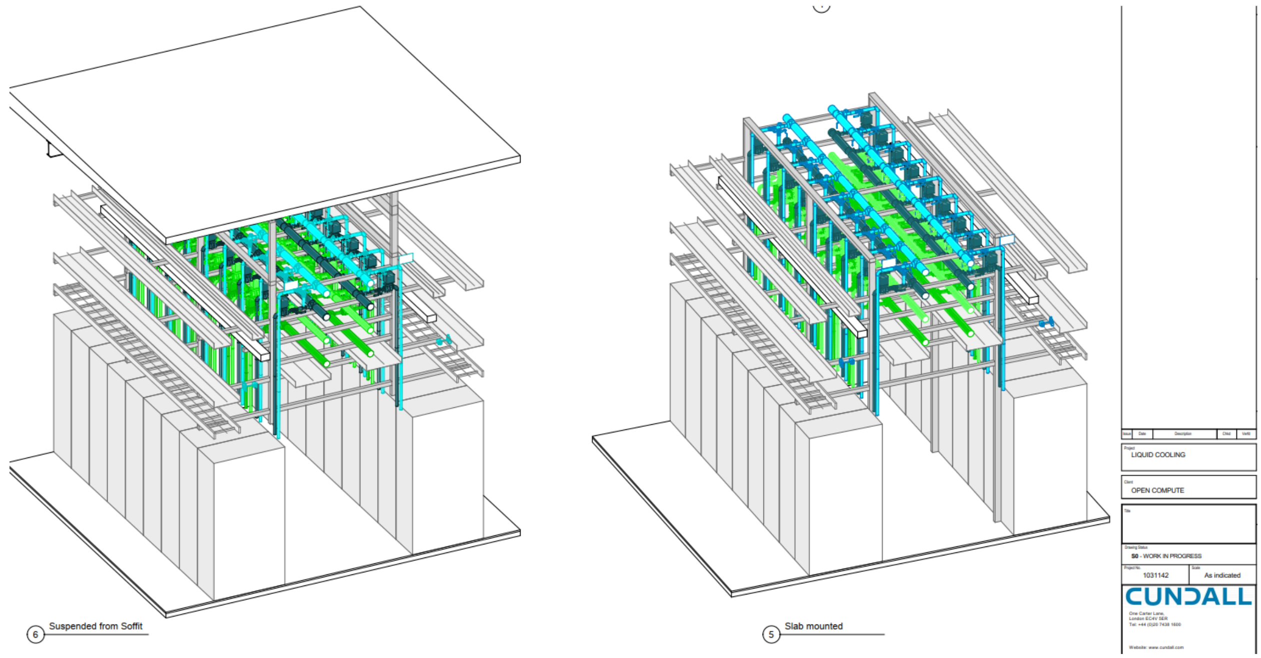
Pipe Size		Stainless Sched 10 Pipe + Fluid	Butterfly Valve Weight Estimates		2' (1 Rack) Module Isolation @ ends		4' (2 Rack) Module Isolation @ ends	
NPS (In)	DN (mm)	Pipe & Fluid Weight Per Foot (lb/ft)	Flanged BFV + 2 flanges	Grooved BFV + 2 couplings	Flanged Valve	Coupling Valve	Flanged Valve	Coupling Valve
3"	80	8.2	31	13	47	29	64	45
4"	100	12.1	52	21	76	45	100	69
6"	150	23.7	69	38	116	86	164	133
8"	200	38.1	129	67	205	143	281	220

- **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.

- **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.

Figure F.1 TCS Structural Considerations - Loading, Clearance, Cables, Leak Detection



Underfloor Pipe Distribution Options:
Adding underfloor liquid distribution to IT racks in a data center 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.

Maintenance and Accessibility:
- Design the system with maintenance in mind, ensuring easy access to components for inspections, repairs, 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, and fire suppression systems.

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 on 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: It may be desirable to incorporate prefabricated modular pipework assemblies into an integrated skid, or frame, that provides pipework support and expansion guides/anchor points. Common framework can also be integrated with other prefabricated assemblies providing fixing points for lighting, sprinkler pipework, cable/fibre trays and bus bars.

At higher operating temperature ranges e.g. W40, W45 and W+ classes, it might also be necessary to include thermal insulation to minimize heat loss into the technical space. This further emphasizes the advantage of a prefabricated, modular system, as pipework could be delivered pre-insulated in its skid, possibly with leak detection tape run beneath insulation, if that is desired by the Owner.

Fig F.1, F.2 - Examples of Prefab, Skid based modular deployment of TCS Systems

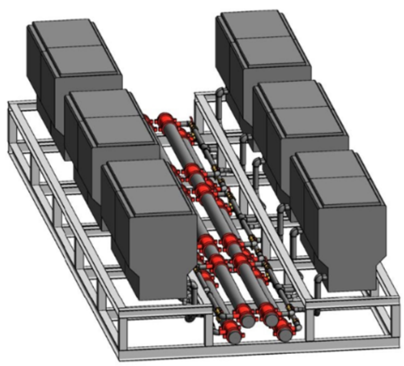


Fig F.1 - JM Gross Engineering,

Appendix G: Commissioning Considerations - Fabrication, Construction, Maintenance

TCS systems have exceptional requirements in cleanliness (25 μ filtration), integrity (no leakage) and performance. Commissioning is the process to validate achievement of these requirements. ASHRAE Guideline 0 covers five commissioning levels: Factory Testing, Delivery and Pre-Installation Testing, Pre-Commissioning and Pre-Functional Start-up, System Functional Performance Testing, and Integrated System Testing.

To ensure successful performance at level 5, Integrated System testing, pipe system assemblies could be cleaned, leak tested, and performance tested at a fabrication site, then sealed, shipped and installed. During installation, retain sealing systems on piping sections until the final connections are made, and ideally avoid joining sections while pollutants that may enter the pipe are present. Cleaning and testing after installation will still be recommended, but with the benefit of lower levels of contamination and lower failure rates.

Offsite pre-installation commissioning and cleaning provides several key advantages:

- **Reliability & quality control** - Job-site discovery of quality and performance issues is very costly, with potential impact of project delay, engineering changes and significant supply chain costs. Performance and integrity testing at the fabrication site optimizes design and quality control with much lower cost and project impact.
- **Sustainability** - Fabrication shops can optimize manufacturing and waste management processes - reducing labor, waste, energy usage, and maximizing waste recycling processes. Chemicals and waste fluids used in cleaning and treatment of pipe systems can be collected and processed with the most sustainable methods.

Cleanliness to 25μ filtration - Achievement of 25μ filtration cleanliness is a major challenge for cloud scale pipe system construction and operation. Standardized procedures (MOPs) will be needed to maintain cleanliness during maintenance.

Pre-commissioning of modules at fabrication site (general guidance)

- **Welding Standard:** Welding to be in accordance with ASME B31.3, "Process Piping", Fluid Service Category D.
- **Deburring** - Exposed edges to be deburred and meet safe handling spec UL1439.
- **Passivation** - Header assemblies should be passivated per ASTM A967.
- **Electropolishing** - Header assemblies should be electropolished per ASTM B912 and flushed with de-ionized water.
- **Hydrostatic Pressure test** - Header assemblies should be hydrostatically pressured to 100±2psi.
- **Packaging** - To avoid contamination in transit, header assemblies should be packaged and sealed, preferably in clear plastic.
- **General cleanliness** - Header assemblies should be free of oil, grease, dirt, burrs, corrosion and other foreign materials or defects.
- **Certification** - It is recommended that “pre-commissioning” tests be certified in writing along with a signed report of pressure test observations.

